

user,<sup>41</sup> and that growth in mobile bandwidth slows to match the growth rate in fixed after five years, fixed service will account for 73% of traffic across the modeled period. Based on these assumptions for traffic allocation, the model allocates 73% of cost to fixed traffic. In other words, the model assumes that mobile carriers can allocate 27% of the build out and operations cost to mobile products, reducing the cost of providing fixed service. If the costs were evenly divided such that 50% of the cost is allocated to fixed and 50% to mobile, the Investment Gap for wireless would decrease to \$10.8 billion. If 100% of the cost were allocated to fixed, the Investment Gap for wireless would increase to \$15.8 billion.

Offsetting these cost savings is the fact that existing operators may not have significant incremental mobile revenue. The assumption in the model is that there is no incremental mobile revenue within the assumed 4G footprints as defined above (i.e., the carrier does not gain new mobile revenue by building out a network capable of providing 4/1 Mbps fixed service). In other words, the model (conservatively) assumes that a wireless carrier will not increase its share of mobile revenue by adding fixed service.

Outside the assumed 4G footprint, there is no allocation issue: all revenue (fixed and mobile) and all costs are incremental in these areas. The model calculations, therefore, include both fixed and mobile revenue, and 100% of the cost of building and operating the network in those areas outside the 4G footprint.

If one does not allocate some fraction of cost to mobile traffic—if, in other words, one requires the fixed network to provide

returns without the benefit of mobile revenue—the Investment Gap for wireless grows to \$16.5 billion. On the other hand, the overall Investment Gap, which is set by the second-least-expensive technology, moves very little, to \$25.6 billion.

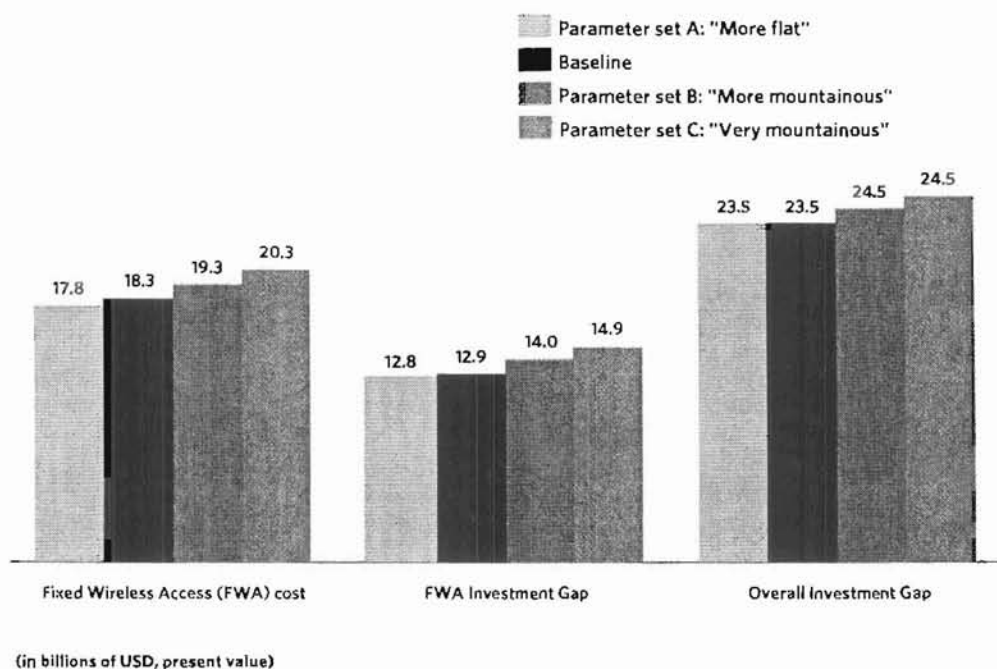
A new entrant would not have the same starting point. All revenue and all cost would be incremental for a new operator. However, within the 4G footprint, a new operator would face competition in both fixed and mobile markets—and would, therefore, have lower take rate and/or ARPU (as noted above).

Outside the 4G footprint, the Investment Gap calculation is relatively straightforward. Whoever provides broadband service will need to assume all deployment costs and will benefit from both fixed and mobile revenues—though carriers are likely to face some amount of (at least 2G) competition for mobile revenue.<sup>42</sup> Inside the 4G footprint, the gap calculation is more complex. For a major wireless company, likely to build out some amount of 4G commercially, the calculation needs to focus on incremental revenue—revenue for fixed service;<sup>43</sup> and incremental cost—the cost for upgrading to offer 4 Mbps downstream, 1 Mbps upstream service.

#### **Assumption: Disbursements will be taxed as regular income just as current USF disbursements are taxed.**

Generally, gross income means all income from whatever source derived.<sup>44</sup> Therefore, taxpayers other than nonprofit or governmental entities must include governmental grants in gross income absent a specific exclusion. In certain circumstances, governmental grants to a corporation<sup>45</sup> may qualify for

*Exhibit 3-Z:  
Sensitivity of  
Build-Out Cost  
and Investment  
Gap to Terrain  
Classification  
Parameters<sup>46</sup>*



exclusion from gross income as a non-shareholder contribution to capital under section 118 of the Internal Revenue Code. In *United States v. Chicago, Burlington & Quincy Railroad Co.*, 412 U.S. 401 (1973), the Supreme Court adopted a two part inquiry to identify a non-shareholder contribution to capital: (1) the contributor motivation test and (2) the economic effect of the transferee test. The transferor's intent must be to enlarge the transferee corporation's capital to expand its trade or business for the benefit of the community at large and not to receive a direct or specific benefit for the transferor. For the requisite economic effect on the transferee corporation, the following five factors must be present:

- The contribution becomes a permanent part of taxpayer's working capital structure
- The contribution may not be compensation, such as direct payment for specific, quantifiable service provided for transferor by transferee
- The contribution must be bargained for
- The contributed asset must foreseeably result in benefit to the transferee in an amount commensurate with its value
- The contributed asset ordinarily, if not always, will be employed in or contribute to the production of additional income<sup>47</sup>

The U.S. Treasury has stated that disbursements that may be used for operating expenses will not qualify as a non-shareholder contribution to capital, while disbursements that are made to a corporation, restricted solely to the acquisition of capital assets to be used to expand the recipient's business—and satisfying the five factors—could be exempt from federal income tax. Such a favorable tax treatment on disbursements could reduce the broadband investment gap by up to \$2.2 billion. Ultimately, the impact of taxes incurred will depend on the disbursement mechanism, as well as the tax situation of the service providers receiving support.

**Assumption: Large service providers' current operating expenses provide a proxy for the operating expenses associated with providing broadband service in currently unserved areas.**

As seen in Exhibits 1-A and 1-B, operating expenses (opex) make up a significant fraction of total costs. Complicating matters is that opex comprises many disparate cost elements: everything from the cost of operating the network (network opex) to the cost of sales and marketing, business support services, power, leases and property taxes (collectively overhead or SG&A). And because each service provider operates differently—there are no standards for how many lawyers,

administrative-support staff or network technicians a company needs to hire per mile of plant or number of customers—it is not possible to calculate opex in a “bottom-up” approach.

To find a reasonable approximation of the opex associated with these networks, the team compiled publicly available data sources and ran a series of regressions. These regressions calculate the relationship between opex and already-calculated quantities like revenue or network capex (see CostQuest documentation for more information). Separate regressions are run for cable, telco and wireless companies; for each network type, opex is broken out according to the categories available in the data sources.

For each opex category, the analysis calculates the primary driver (i.e., the known quantity that most strongly correlates with the opex category). Thus some opex categories, like telco network opex, are driven off of network investments; wireless tower operations costs are driven off site counts; while other costs, such as marketing or bad debt, are calculated as a function of revenue. The ratio between the driver and the opex category (the coefficient of the regression) is calculated for different size operators in different geographies, though in some cases the impact of these factors is negligible.

Using this approach to estimate the real-world opex of actual companies (the same opex and companies that formed the source data) suggests that the approach is reasonable. Variations between the calculated and actual values of opex ranged from less than 1% to roughly 10%, depending on the cases studied.

Throughout the calculations described above, we assume that the opex associated with large telco and wireless providers is appropriate. If one instead assumed that a small telco and small wireless operator provided service, the gap would grow to \$26.4 billion.<sup>48 49</sup>

## CHAPTER 3 ENDNOTES

- <sup>1</sup> *In the Matter of Representing the Authorized Rate of Return for Interstate Services of Local Exchange Carriers*, CC Docket No. 89-624, Order, 5 FCC Red 7507 (1990).
- <sup>2</sup> Note that model runs completed with a shorter time horizon (see User Guide for more information) will not include a terminal value. They will, instead, accelerate the depreciation and replacement of longer-lived assets, effectively requiring returns on those long-life assets in a shorter period of time.
- <sup>3</sup> Note that for census blocks with the largest area (likely the lowest-density census blocks): even census blocks may be too aggregated. See, for example, "State Broadband Data and Development Grant Program; Notice of Funds Availability, Clarification," 74 Federal Register 154 (12 Aug. 2009), pp. 40569-40570.
- <sup>4</sup> Cable deployments are all new deployments that expand the cable plant; therefore all revenue is incremental.
- <sup>5</sup> HFC and FTTP networks also have scale lengths associated with them related to the distances of signal propagation in coaxial cable and fiber.
- <sup>6</sup> Verizon's LTE field trials in Boston and Seattle have shown average downlink rates of 5Mbps to 12Mbps and average uplink speeds of 2Mbps to 3Mbps at the time of this writing. See [http://www.computerworld.com/s/article/9167258/LTE\\_speeds\\_faster\\_than\\_expected\\_in\\_Verizon\\_trials](http://www.computerworld.com/s/article/9167258/LTE_speeds_faster_than_expected_in_Verizon_trials).
- <sup>7</sup> CITI BROADBAND REPORT AT 57.
- <sup>8</sup> In this example, we assume that the two networks are owned and operated by different entities. The cost impact of supporting two networks may be less severe in cases in which one company owns both networks.
- <sup>9</sup> The gap, specifically, is built from the second-least-expensive technology in each county across the country. Wireless with no competitors is used in all geographies; 12,000-foot-loop FTTN with one competitor is used in areas assumed to have 4G service, and with no competitors in other areas. See "Creating the base-case scenario and output" at the end of Chapter 1.
- <sup>10</sup> *High-Cost Universal Service Support; Federal-State Joint Board on Universal Service*, WC Docket No. 05-337, CC Docket No. 96-45, Notice of Proposed Rulemaking, 23 FCC Red 1495, para. 11 (2008).
- <sup>11</sup> The National Broadband Plan recommends identifying "ways to drive funding to efficient levels, including market-based mechanisms where appropriate."
- <sup>12</sup> The retail price of satellite service could exceed the price of terrestrial broadband. A "buy down" would ensure that those receiving satellite-based services would not face higher monthly rates than those served by terrestrial providers in other geographies. There is a sample buy-down calculation in Satellite portion of Chapter 4.
- <sup>13</sup> Satellite broadband and its ability and capacity to provide terrestrial-replacement service are discussed in Chapter 4.
- <sup>14</sup> See broadband-speed assumption section. See also Omnibus Broadband Initiative, *Broadband Performance* (OBI Working Paper, forthcoming) (Bowen, *Broadband Performance*).
- <sup>15</sup> All speeds throughout this paper are "actual" speeds. As with the National Broadband Plan itself, "actual speed" refers to the data throughput delivered between the network interface unit (NIU) located at the end-user's premises and the service provider Internet gateway that is the shortest administrative distance from that NIU.
- <sup>16</sup> See OBI, *Broadband Performance*.
- <sup>17</sup> Note that there were not enough data to complete an accurate predictive model of DSL actual speeds above 6 Mbps; therefore for speeds above 6 Mbps, the cable footprint is taken as the footprint of served housing units without augmentation from telco plant.
- <sup>18</sup> comScore, Inc., Jan.-June 2009 Consumer Usage database (sampling 200,000 machines for user Web surfing habits) (on file with the FCC) (comScore database).
- <sup>19</sup> Horrigan, John. *Home Broadband Adoption 2009*. Pew Internet & American Life Project: June 2009. See [http://www.pewinternet.org/-/media/Files/Reports/2009/Home\\_Broadband\\_Adoption-2009.pdf](http://www.pewinternet.org/-/media/Files/Reports/2009/Home_Broadband_Adoption-2009.pdf).
- <sup>20</sup> Vanston, Lawrence K. and Vanston, John H. *Introduction to Technology Market Forecasting*. Austin, TX: Technology Futures, Inc. 1996. Note that we considered the Fisher-Pry model but ultimately concluded that, since it is geared toward modeling the substitution of a superior technology for an inferior one, it was not appropriate to use in this instance.
- <sup>21</sup> Geometrically speaking, the inflection point on the cumulative curve is the point at which the curve moves from convex to concave. The slope of the tangential line along the cumulative curve is highest at the inflection point, indicating maximum acceleration of adoption. Mathematically, the incremental curve is the first derivative of the cumulative, and the inflection point is at the maximum slope of the cumulative or maximum of the incremental curve.
- <sup>22</sup> Note that these calculations represent the investment gap for each individual technology: the \$23.5 billion base case takes the second-lowest-gap technology in each county as described above, not the gap for any one technology.
- <sup>23</sup> Because we lacked precise data on the location of existing FTTP deployments, the figures for FTTP cost and investment gap are for a run that covers the entire country. Actual costs and gap would be reduced by the roughly 17 million HUs that are already passed by FTTP facilities.
- <sup>24</sup> The best fit between modeled data (Gompertz) and observed data (Pew), in its least-squares sense, is an instance of the model for which the sum of squared residuals has its least value, where a residual is the difference between an observed value and the value provided by the model.
- <sup>25</sup> Each period on the x-axis represents one year, with the inflection point at zero.
- <sup>26</sup> Note that some demographic data, such as income, are calculated only at the census block group level, these geographically coarser data are applied "down" to the subordinate census blocks.
- <sup>27</sup> For Telco: 1) Proprietary CostQuest information and industry data/financials (publicly available) 2) Table 5 from FCC's June 30, 2008 Broadband Report. For Wireless: 1) <http://wirelessfederation.com/news/17341-atl-adds-1.4mn-mobile-subscribers-in-q2-usa/> (last accessed Mar. 24, 2010) 2) See SNL Kagan (a division of SNL Financial LC), "U.S. 10 year mobile wireless projections" 3) FCC "High Speed Lines by Information Transfer Rates" as of June 30, 2008. For Cable: 1) See SNL Kagan (a division of SNL Financial LC), <http://www.snl.com/interactivex/CableMSOOperatingMetrics.aspx> (Login required) templates that contained Q1 2004 - Q2 2009 data for: Basic Penetration, Basic Subscribers, Basic Homes Passed, Video Penetration Rates, Video Subscribers, Video Homes Passed, HSD Penetration Rates, HSD Subscribers, HSD Homes Passed, Voice Penetration Rate, Voice Subscribers, Voice Home Passed 2) See SNL Kagan (a division of SNL Financial LC), "Cable TV Projections, 2008-2019" 3) Publicly available financials for the cable companies, including RCN, Knology, and General.
- <sup>28</sup> For Telco: Data were obtained from publicly available AT&T investor reports on U-VERSE ([http://www.att.com/Common/merger/files/pdf/3Q09\\_U-verse\\_Update\\_10.22.pdf](http://www.att.com/Common/merger/files/pdf/3Q09_U-verse_Update_10.22.pdf)) as well as proprietary CostQuest information. For Cable: Data were obtained from Forester, Williams, Douglas, et al. "MULTI-PLAY SERVICES: Driving Subscriptions in a Maturing Market and Down Economy", Volume 2, 2008. For Wireless: Data were obtained from the Wireless Federation article, <http://wirelessfederation.com/news/17341-atl-adds-1.4mn-mobile-subscribers-in-q2-usa/> (last accessed Mar. 24, 2010).
- <sup>29</sup> See, for example, SNL Kagan (a division of SNL Financial LC), "Cable TV Projections, 2008-2019".
- <sup>30</sup> Dutz, Mark, Jonathan Orszag, and Robert Willig, "The Substantial Consumer Benefits of Broadband Connectivity for US Households," (July 14, 2009). See [http://innovation.oregon.gov/files/special-reports/CONSUMER\\_BENEFITS\\_OF\\_BROADBAND.pdf](http://innovation.oregon.gov/files/special-reports/CONSUMER_BENEFITS_OF_BROADBAND.pdf).
- <sup>31</sup> See FCC, Industry Analysis and Technology Division, Wireline Competition Bureau, *Trends in Telephone Service Report* ("Trends in Telephone Service Report, Table 3.2 & 7.1 (August 2008), available online at [http://hraunfoss.fcc.gov/edocs\\_public/attachmatch/DOC-284932A1.pdf](http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-284932A1.pdf)).
- <sup>32</sup> See FCC, Industry Analysis and Technology Division, Wireline Competition Bureau, *Trends in Telephone Service Report* ("Trends in Telephone Service Report, Table 13.3 (August 2008), available online at [http://hraunfoss.fcc.gov/edocs\\_public/attachmatch/DOC-284932A1.pdf](http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-284932A1.pdf)).
- <sup>33</sup> See FCC, Industry Analysis and Technology Division, Wireline Competition Bureau, *Trends in Telephone Service Report* ("Trends in Telephone Service Report, Table 1.2 (August 2008), available online at [http://hraunfoss.fcc.gov/edocs\\_public/attachmatch/DOC-284932A1.pdf](http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-284932A1.pdf)).
- <sup>34</sup> In the Matter of Implementation of Section 3 of the Cable Television Consumer Protection and Competition Act of 1992 Statistical Report on Average Rates for Basic Service, Cable Programming Service, and Equipment, MM Docket No. 92-266, 21 FCC Red 2503 (December 2006) available online at [http://hraunfoss.fcc.gov/edocs\\_public/attachmatch/FCC-06-179A1.pdf](http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-06-179A1.pdf).
- <sup>35</sup> See FCC, Industry Analysis and Technology Division, Wireline Competition Bureau, *Trends in Telephone Service Report* ("Trends in Telephone Service Report, Table 3.1 (August 2008), available online at [http://hraunfoss.fcc.gov/edocs\\_public/attachmatch/FCC-06-179A1.pdf](http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-06-179A1.pdf)).

## CHAPTER 3 ENDNOTES

fcc.gov/edocs\_public/attachmatch/DOC-284932A1.pdf. See also In the Matter of Implementation of Section 3 of the Cable Television Consumer Protection and Competition Act of 1992 Statistical Report on Average Rates for Basic Service, Cable Programming Service, and Equipment, MM Docket No. 92-266, 21 FCC Rcd 2503 (December 2006) available online at [http://hraunfoss.fcc.gov/edocs\\_public/attachmatch/FCC-06-179A1.pdf](http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-06-179A1.pdf).

<sup>39</sup> Tuning a propagation model involves significant drive testing to ensure simulated signal density correctly accounts for foliage, buildings, terrain and other factors which result in attenuation.

<sup>40</sup> Cisco Ex-Parte Filing: A National Broadband Plan for Our Future, GN Docket No. 09-51, Cisco VNI Mobile Data (FCC filed 25 March, 2010)

<sup>41</sup> ComScore 200,000 panel of machine survey (Jan-Jun 2009).

<sup>42</sup> Cisco Ex-Parte Filing: A National Broadband Plan for Our Future, GN Docket No. 09-51, Cisco VNI Mobile Data (FCC filed 25 March, 2010).

<sup>43</sup> See OBI, Broadband Performance.

<sup>44</sup> 2:1 assumption based on the average number of people per household and wireless penetration.

<sup>45</sup> While the mobile voice ARPU of a user is \$37 per month in model calculations, assuming one competitor on average in non-4G areas leads to a weighted-average mobile voice ARPU of \$18.50

<sup>46</sup> Assuming, in other words, that a national carrier will not gain incremental revenue from deploying a fixed-broadband network.

<sup>47</sup> 26 U.S.C. § 61(a).

<sup>48</sup> Includes Limited Liability Companies (LLCs) treated as a corporation for federal income tax purposes. This tax treatment would not apply to noncorporate entities such as partnerships, including LLCs treated as a partnership for federal income tax purposes

<sup>49</sup> The baseline classification is based on parameters in Exhibit 4-K in the following section. The remaining parameter sets alter the classification of flat and hilly terrains, as shown in Exhibit 4-Y. We highlight the changes in the parameters from the baseline for convenience.

<sup>50</sup> Letter from William J. Watkins, Chief Counsel, U.S. Department of Treasury, to Cameron K. Kerry, General Counsel, U.S. Department of Commerce (Mar. 4, 2010).

<sup>51</sup> The model attempts to capture the scale effects of operations by examining publicly available data. It is possible that there are additional scale effects not captured in this calculation, or that smaller companies could face costs even higher than in the source data.

<sup>52</sup> This gap value is different from Exhibit 3-G. In this example, since we are comparing against the base case, the telco faces one competitor in 4G areas and zero in non-4G areas. Exhibit 3-G assumes the telco faces zero competitors in all areas.



## IV. NETWORK ECONOMICS

The United States has a diversity of both wired and wireless broadband networks which provides the vast majority of Americans with choices as to their broadband providers: most homes have a choice between wired broadband provided by a telephone network or a cable network. Telephone and cable networks were originally built for and funded by voice and video services respectively; but now, through upgrades, both are able to provide high-speed broadband to much of the country. Large investments in these networks are being made to further increase speed and capacity in the most profitable areas of the country. In addition to wired networks, there have been significant investments in wireless networks to provide broadband terrestrially via mobile and fixed wireless networks or via satellite. Like wired broadband, mobile broadband is likely to be provided over a network originally built for a different purpose—in this case mobile voice. Strong 3G mobile broadband adoption from smartphones, data cards and netbooks has driven operators to commit to large-scale upgrades to their wireless data networks using new 4G technologies. These new 4G technologies (WiMAX and LTE) can be used to provide broadband in higher speed mobile networks, fixed wireless networks and even hybrid fixed/mobile networks. Due to high costs and low capacity, satellites have primarily targeted customers in remote areas without other broadband options, but recently developed high-throughput satellites may change this.

### BASIC NETWORK STRUCTURE

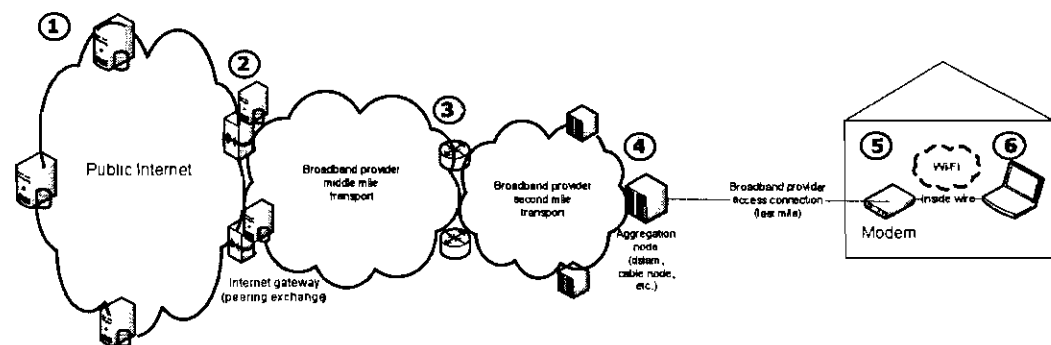
Exhibit 4-A is a diagram of the different portions of a broadband network that connect end-users to the public Internet. Starting at the public Internet, (1) content is sourced from various geographies and providers, data flow through the first peering point of the broadband provider (2), through the “middle mile” aggregation point (3) and “second mile” aggregation point (4), before being transported over either a wired or wireless “last mile” connection to the customer modem (5), which can either be embedded in a mobile device or standalone customer premise equipment (CPE), in the case of a fixed network. Once inside the premises broadband is connected to a device (6) through either wired or wireless connections (e.g. Wi-Fi).

### LAST-MILE TECHNOLOGY COMPARISON

We model the deployment economics of DSL/FTTN, FTTP, HFC, Satellite and 4G fixed wireless technologies. Each technology is modeled separately using detailed data and assumptions. Our model shows that fixed wireless and 12,000-foot-loop DSL have the best economics in delivering 4 Mbps down- and 1 Mbps up-stream to the unserved areas of the country.

Fixed wireless networks have favorable economics in most unserved areas, as the high fixed costs of wireless towers are amortized over many customers. In the least dense areas, particularly in mountainous terrain, however, there are few customers per tower and wired technologies are more economically efficient. Among wired networks, 12 kilofeet (kft) DSL has the best economics while still meeting the National Broadband Availability Target because it requires the least amount of network replacement/building. Although satellite capacity is

*Exhibit 4-A:  
Basic Network  
Structure*



#### DEFINITIONS

- ① **Public Internet content:** Public Internet content that is hosted by multiple service providers, content providers and other entities in a geographically diverse (worldwide) manner
- ② **Internet gateway:** Closest peering point between broadband provider and public Internet for a given consumer connection
- ③ **Link between second mile and middle mile:** Broadband provider managed interconnection between middle and last mile
- ④ **Aggregation node:** First aggregation point for broadband provider (e.g. DSLAM, cable node, satellite, etc.)
- ⑤ **Modem:** Customer premise equipment (CPE) typically managed by a broadband provider as the last connection point to the managed network (e.g. DSL modem, cable modem, satellite modem, optical networking terminal (ONT), etc.)
- ⑥ **Consumer device:** Consumer device connected to modem through internal wire or Wi-Fi (home networking), including hardware and software used to access the Internet and process content (customer-managed)

limited by the number of satellites, and latency can be an issue for some applications, the fact that costs are not dependent on population density makes it an attractive option for serving the most remote areas of the country. We model FTTP, HFC and 3-5 kft DSL as well, and even though the performance and revenue opportunities are better with these technologies, they have unfavorable economics in areas with low population density relative to the other technologies mentioned, due to the high fixed costs of building or replacing large parts of the network.

In order to accurately model each technology, we need to understand both the technical capabilities as well as the economic drivers. First, we determine which of the network technologies could meet end-user speed requirements. Then, we collect detailed cost data required to accurately model the build of a network with the required network capacity. Finally, we determine the incremental revenues that could be generated from each technology.

### Network Capabilities

The National Broadband Availability Target is download speeds of 4 Mbps and upload speeds of 1 Mbps. As we shall see in later sections, we dimension the DSL/FTTN, HFC, FTTP, fixed wireless and satellite networks in our network model to meet the National Broadband Availability Target. Further, the sustained data rate capabilities of the networks are comparable.

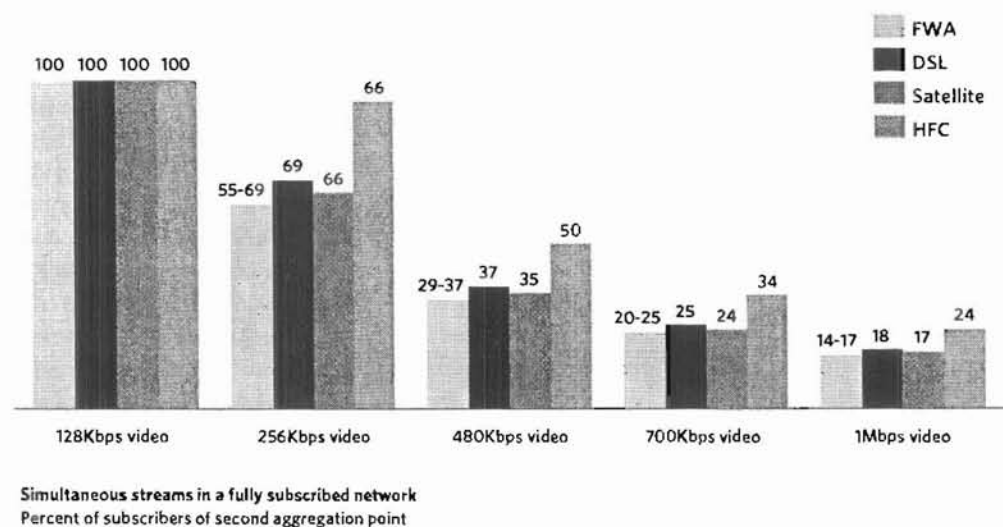
For example, we compare the streaming capacities of the DSL, wireless, HFC and satellite networks as modeled in our analysis in Exhibit 4-B. For each of the cases, we consider a fully subscribed network, i.e., a network with the maximum

prescribed subscriber capacity at the aggregation point nearest the end-users (a cell site in the case of wireless, a DSLAM/backhaul for DSL and a spot-beam for satellite). The details for each technology will be presented in following sections. For this analysis we assume the following: for wireless, a network of cell sites with 2x20MHz of spectrum, each with 650 subscribers;<sup>1</sup> for DSL, a network with about 550 subscribers<sup>2</sup> being served by a Fast-E second-mile backhaul link.

The exhibit shows the percentage of subscribers in each network that can simultaneously experience video streams of various rates. Thus, for example, we estimate that 29-37% of the wireless subscribers in the cell site can simultaneously enjoy a 480 kbps video stream.<sup>3</sup> For DSL and next-generation satellites, those numbers are 37% and 35%, respectively. So, each of the networks as dimensioned has comparable capabilities. We note that the capacity of an under-subscribed or under-utilized network will, of course, be higher. Thus, for example, if we used a Fast-E backhaul to serve a single 384-port DSLAM, then nearly 55% of subscribers can simultaneously enjoy a 480 kbps video stream.

However, the methods by which each technology can expand to meet growing capacity demand in the last mile differ. For example, with DSL, increased demand can necessitate two types of capacity upgrades that have very different remedies. First, when speed needs for a given user exceed the loop length capabilities on a DSLAM port (unshared network portion), the DSLAM is extended closer to the user so that the shortened copper loop can provide higher speed. This will involve fiber extension, electronics upgrades and significant outside plant reconstruction and rearrangement. This can be a very costly

*Exhibit 4-B:  
Streaming Capacity  
of Modeled  
Broadband  
Networks<sup>4</sup>*



process that involves many aspects of “new” construction, such as pole transfers/make-ready costs, fiber trenching and general overbuild of portions of the outside plant. And second, if the capacity expansion is a result of aggregate demand growth among the users sharing the second-mile backhaul of the network, and not the last mile, one only needs to upgrade DSLAM ports and increase backhaul capacity. Undoubtedly, this carries significant cost, but is relatively straightforward as it primarily involves electronics upgrades.

In the case of HFC, RF signals for data transmission are modulated onto coaxial cables and shared among all of the subscribers who are connected and active on the coaxial portion of the HFC network. Therefore, the last mile is a shared resource. One process for capacity expansion is cable node splitting, which involves electronics upgrades similar to DSL but often also requires significant outside plant reconstruction and rearrangement. Thus, it involves many aspects of “new” cable construction, such as pole transfers/make ready costs, fiber trenching and general overbuild of portions of the outside plant. While this process is not without significant cost and lead time, it is well understood and has been practiced for several years. In addition, there are a number of other often-used methods for increasing capacity as will be discussed in the HFC section.

Similarly, the last mile is shared in FTTP/PON networks. More precisely, optical signals are modulated onto fiber optic cables, which are then distributed to individual homes between the PON splitter and the home. Capacity expansion is again a matter of upgrading electronics either at the headend, home or both, and certainly requires rearrangement of PON splitters and other passive outside plant equipment but does not require a fundamental design and architecture change.

In the case of wireless communications, the primary shared resource in the last mile is the RF spectrum. Multiple wireless devices, such as mobile phones and wireless data cards, simultaneously transmit/receive over the same shared spectrum. In fact, an average cell site covers more than 4,000 people, often referred to as POPs or population.<sup>5</sup> As we will see later, the wireless networks that we model to deliver broadband will be capable of serving up to 650 homes per cell tower using a paired 2x20 MHz<sup>6</sup> of spectrum. Capacity expansion in the last mile typically involves using more spectrum or adding more cell sites or both.<sup>7</sup> Since wireless spectrum is a scarce resource, wireless capacity expansion can be expensive, involving many of the high costs of outside plant/tower construction, etc. (similar to wired technologies discussed above), unless the provider has adequate spectrum holdings. With adequate spectrum, however, capacity expansion is straightforward and relatively inexpensive. Spectrum needs in *unserved rural areas*—with low population densities—are expected to be limited. Given the amount of spectrum currently available and the additional

spectrum likely to become available in the next several years,<sup>8</sup> we expect that capacity expansion in wireless should be relatively inexpensive in *these* areas.

Capacity expansion with satellites will ultimately involve launching additional satellites which are capable of providing more total bandwidth and higher spatial reuse of the available spectrum. New launches, however can cost up to \$400 million and require potentially long lead times, as will be discussed later in this chapter.

All of the technology comparisons in this chapter are based on network builds that can meet the target, with an effective busy hour load assumption of 160 kbps (see later section on Network Dimensioning). A fundamental tenet is that the networks have been modeled such that users will receive an equivalent level of service and performance whether they are serviced by the fixed wireless 4G access network or a 12 kft DSL architecture.

### Cost Comparison

Our model allows us to calculate the relative cost structure of different last mile technologies as a function of population density in unserved areas. As shown in Exhibit 4-C, the costs associated with all technologies are competitive in the highest densities and diverge as we move toward lower population densities. Note that Exhibit 4-C represents the present value of costs, not the gap associated with each technology.

HFC and FTTP costs are comparable and both are among the most costly in all densities. As one might expect, the cost of running a new connection to every home in low-density areas is very high. In effect, carriers face the cost of deploying a green-field network in these areas.

Short-loop FTTN deployments (3,000- and 5,000-foot loops) realize some cost savings relative to FTTP from being able to avoid the last few thousand feet of buildout. These savings are particularly valuable in denser areas where operators are more likely to find more homes within 3,000 or 5,000 feet of a given DSLAM location. At the other extreme, in the least-dense areas, where a carrier might have only one customer within 3,000 feet of a DSLAM location, 3,000-foot FTTN is actually more expensive than FTTP; a fiber drop is less costly than a DSLAM. Longer-loop (12,000-foot) DSL is particularly low cost in higher-density areas, where the cost of a DSLAM can be amortized over more customers.

Wireless solutions are among the lowest cost solutions and wireless costs grow less quickly as density falls. As discussed in Chapter 3, and in more detail below, a major driver of wireless cost is cell size. The assumptions made about cell size in hilly terrain are larger drivers of cost than density; however, when ordering census blocks by density, as in Exhibit 4-C, this effect is averaged away and lost. More detail about the impact of cell



size on cost is included later in this chapter.

Exhibit 4-C includes only costs, both capex and ongoing costs, and does not include revenue. Technologies that enable higher revenue could have lower investment gaps than costlier alternatives. Thus, it is possible that FTTP deployment could have a lower investment gap in some census blocks than FTTN or wireless. In addition, given the assumptions made about take rate and ARPU, wireless often will have a lower investment gap than a less-costly 12,000-foot-DSL solution.

However, as noted in Chapter 3, evaluating the economics of technologies over areas as small as a census block makes little sense. Counties or other service areas draw census blocks from across multiple densities. Therefore this revenue-driven advantage is muted when census blocks are aggregated into counties or other service areas and wireless and 12,000-foot-loop DSL are the lowest investment-gap terrestrial solutions overall.

### TECHNOLOGIES INCLUDED IN THE BASE CASE

As seen in Exhibit 4-C, our model indicates fixed wireless and 12 kft DSL are the low-cost terrestrial solutions that are capable of delivering speeds consistent with the Broadband Availability Target in unserved areas. We will focus on those technologies and satellite across the next three sections, before returning to those technologies with higher deployment costs.

### Wireless Technology

The first mobile networks were built when the FCC approved commercial car-phone service in 1946 but the first commercial cellular telephony service in the United States came in 1983 using AMPS technology. AMPS was an analog phone service that was still in use in some regions of the United States as recently

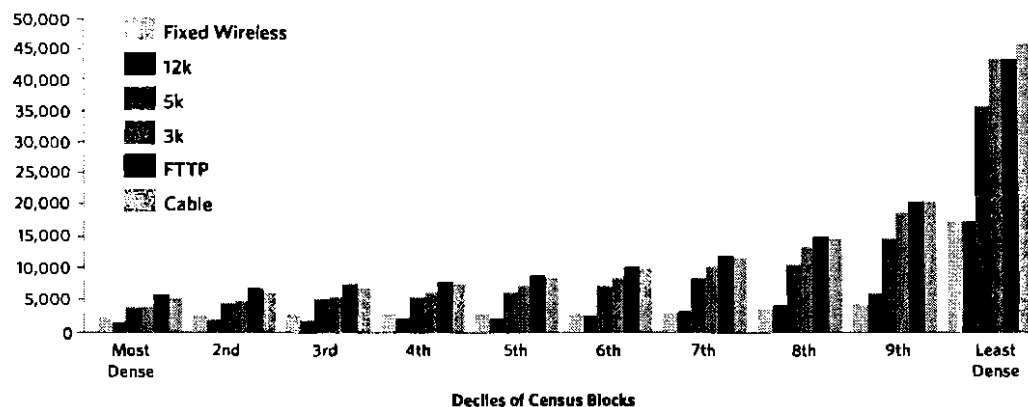
as 2008. As wired communications started going digital in the 1980s, so did wireless telephony. In the 1990s there were four different 2G digital wireless technologies used in the United States: CDMA-based IS-95, TDMA-based IS-54 (often called Digital AMPS or D-AMPS), GSM and iDEN. Initially, these technologies provided voice services and some limited circuit-switched data services like SMS with peak data rates of 9.6 kbps.

CDMA and GSM became the predominant technologies in the United States, with more than 71% of subscribers in 2004.<sup>9</sup> For GSM, the first real step towards packet-based data services was GPRS, which was later replaced by EDGE. Even with EDGE, the average data rates were still only 100-130 kbps. The big step towards mobile broadband for GSM providers came with UMTS or WCDMA, a CDMA-based air interface standard; average user data rates were 220-320 kbps. Over time, the standards bodies created HSDPA for the downlink and HSUPA for the uplink, collectively referred to as HSPA today. User data rates of up to several Mbps became possible,<sup>10</sup> allowing GSM-family providers to offer true 3G service. See Exhibit 4-D.

Like GSM, CDMA rapidly evolved, first into CDMA2000 1xRTT which delivered peak data rates of 307 kbps and later into CDMA2000 EV-DO that is capable of delivering data rates of up to 3.1 Mbps.

There are two competing 4G standards that can be used in wireless broadband networks:<sup>11</sup> LTE, which is an evolution of the GSM family of standards, and WiMAX. Both of these technologies use OFDMA modulation instead of CDMA and, as such, are not backward compatible with either HSPA or EV-DO. The 4G technologies are only beginning to be deployed and adopted. In fact, LTE, one of the most anticipated

*Exhibit 4-C:  
Present Value of  
Total Costs for All  
Technologies in  
Unserved Areas<sup>12</sup>*



Ordered by unserved housing-unit density

4G technologies, has yet to be commercially deployed in the United States as of the time of this writing, while WiMAX covers less than 3% of the population.<sup>13</sup>

### **Evolution of the Performance of Wireless Technologies**

As wireless technologies have evolved, so have their performances. In a broad sense, with every evolution the industry has achieved higher peak throughputs, improved spectral efficiencies and lower latencies. Additionally, with 4G the wireless signal can be transmitted over wider bandwidths of up to 20MHz,<sup>14</sup> which further increases spectral efficiency and network capacity, while letting the user experience higher data rates. Additionally, 4G uses a native, all-IP architecture, thus benefitting from the technology and economic efficiencies of IP networks.

The most important dimension of performance—at least as far as capacity of the wireless network is concerned—is spectral efficiency, which is the number of bits/second that a sector can

transmit per hertz of spectrum. As such, spectral efficiency drives average downlink data capacity of a cell site linearly. Exhibit 4-E shows the evolution of the average downlink and uplink data capacities of a single sector in a three-sector cell site for the GSM family of standards.<sup>16</sup>

Note that there is no known analytic form for Shannon capacity for a multi-user, multi-site wireless network today. However, one can estimate the Shannon limit for a single user on a single cell site. Further, scheduling efficiency gains from multi-user scheduling are well understood.<sup>17</sup> One can therefore estimate the capacity of a multi-user, multi-site network.<sup>18</sup> But, this estimate does not take into account potential future gains in wireless technology and networks from, for example, coordinated transmission of data to users from multiple cell sites. Nonetheless, this estimated limit suggests that gains in spectral efficiency—and the ability of networks to cheaply improve performance or capacity—will likely be limited in the future.

In fact, as illustrated in Exhibit 4-E, we estimate that the latest release of the LTE standard brings us to within 25% to 30% of the maximum spectral efficiency achievable in a mobile network. Going forward, improvements in spectral efficiency are likely to result from techniques that include the use of new network architectures and multiple-antennas.<sup>19</sup> Specifically:

- Multiple-antenna techniques, such as spatial multiplexing in the uplink and improved support for beamforming
- Network enhancements:
  - Coordinated transmission of data to users from multiple cell sites
  - Relays or repeaters to improve coverage and user experience at cell edges with low additional infrastructure cost
- Carrier or spectrum aggregation to achieve higher user burst data rates

The 4G network architecture represents an evolution as well. 3G networks, having evolved from legacy 2G architectures that were primarily designed for circuit-switched traffic, were hierarchical in design and included many more network elements. 4G, on the other hand, optimizes the network for the user plane and chooses IP-based protocols for all interfaces.<sup>20</sup> The result: a much simpler architecture with far fewer network elements. Not only does this reduce capex and opex for 4G networks relative to 3G, but it also means reduced network latencies; see Exhibit 4-F. The performance of TCP/IP, the Internet data transport protocol, is directly impacted by latency,<sup>21</sup> so that reduced latencies translate directly into improved user experiences.

#### **BOX 4-A**

### **Wireless Multiple Access 101**

In any wireless network with multiple users, those users must share the wireless communication channel. Different technologies use different schemes for sharing the channel; these schemes are commonly referred to as multiple access schemes. One such scheme is Time Division Multiple Access, or TDMA, which divides the channel into multiple time slots, allocating each to one of many users. The users then communicate with the base station by transmitting and receiving on their respective time slots. TDMA is used in GSM/GPRS/EDGE as well as the eponymous TDMA IS-54 standard.

Another scheme is Code Division Multiple Access or CDMA. It uses *spread-spectrum* technology for sharing the physical communication channel between the users. More precisely, in CDMA, the signal to and from each user is modulated using a uniquely assigned code. This modulated signal on the assigned code is spread across far more bandwidth than the bandwidth of the data being transmitted. This allows multiple users to simultaneously transmit or receive communication signals on the channel, which are then separated at the base station using the codes. CDMA allows for greater spectral efficiency than TDMA where communication to each user takes place in a uniquely assigned time slot. All 3G technologies, EV-DO and UMTS/HSPA, use CDMA, as does IS-95 and CDMA 1xRTT.

Finally, in Orthogonal Frequency Division Multiplex Access or OFDMA, data transmission occurs on a set of orthogonal *sub-carriers* assigned to each user; the sub-carriers are then modulated and transmitted using conventional modulation techniques. OFDMA has emerged as the multiple access technique for 4G technologies.<sup>15</sup>

Exhibit 4 D:  
Different Wireless  
Technology Families  
Have Evolved Over  
Time<sup>22</sup>

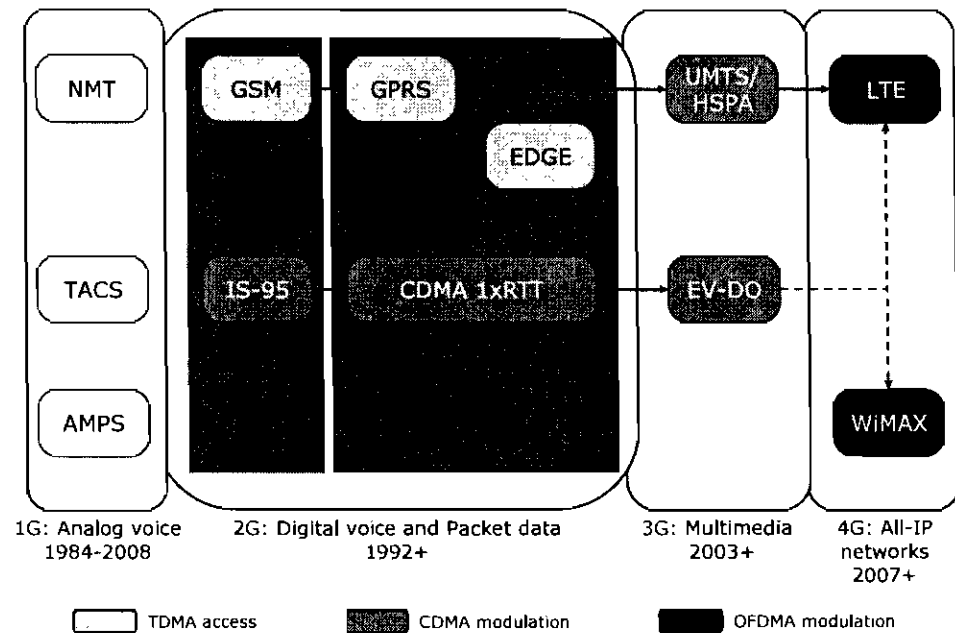
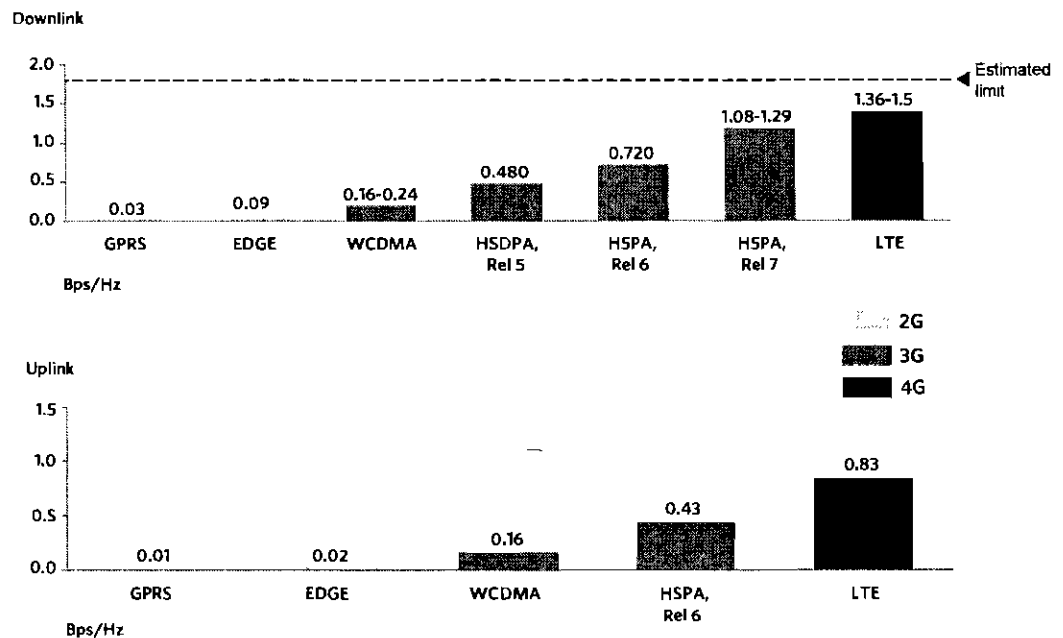


Exhibit 4-E:  
Downlink and  
Uplink Spectral  
Efficiencies by  
Technology<sup>23</sup>



#### 4G Deployment Plans

Exhibit 4-G shows projected 4G deployment plans for major carriers in the United States based on public announcements.<sup>24</sup> Verizon Wireless has the most aggressive deployment schedule for LTE. It plans to build out to 20 to 30 markets in 2010, extending to its entire EV-DO footprint by 2013—thus reaching more than 93% of the U.S. population.<sup>25</sup> AT&T has announced that it will be trialing LTE in 2010, then rolling it out commercially in 2011. Sprint plans to deploy WiMAX through its partnership with Clearwire. WiMAX has been rolled out in a few markets already and Clearwire announced plans to cover 120 million people by the end of 2010. With carriers in the United States and around the world making these commitments to deploy 4G, we expect it to have significant benefits of scale: a robust ecosystem, strong innovation and substantive cost savings.

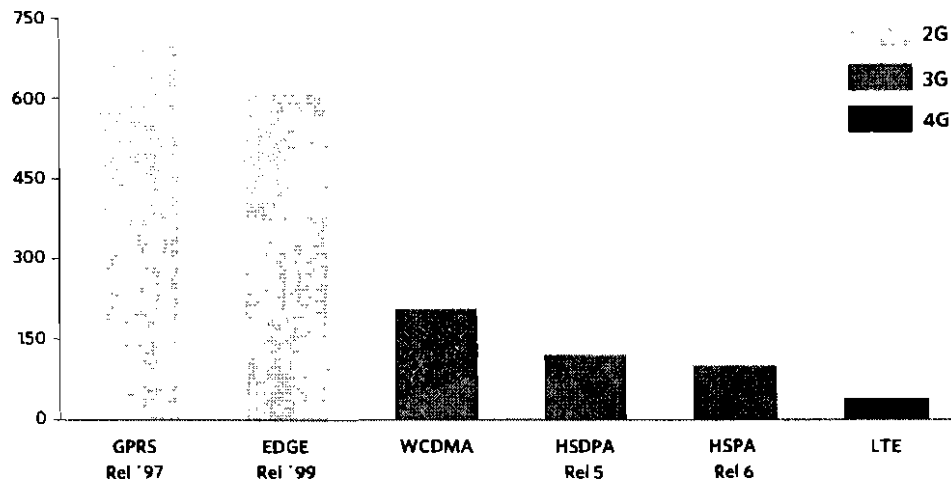
Given the superior performance of 4G and the likely extensive 4G coverage by 2013, we shall limit our wireless analysis

to 4G technologies in the rest of this document. Our goal is certainly not to pick technology winners, and we recognize that other wireless technologies, such as WiFi mesh, cognitive radios and even 3G, will be important parts of the broadband solution. However, these technologies are unlikely to deliver a cost-effective and reliable wide-area broadband experience consistent with the National Broadband Availability Target in unserved communities. To the extent these technologies offer appropriate service at comparable or lower prices, they will certainly play a role.

#### Fixed Wireless Access (FWA) Networks

By FWA networks, we refer to wireless networks that use fixed CPEs in addition to (or, possibly, even instead of) mobile portable devices. FWA solutions have been deployed as a substitute for wired access technologies. For example, FWA networks are being used commercially in the U.S. by Clearwire with WiMAX and Telstra with HSPA, and globally by Telstra

*Exhibit 4-F:  
Evolution of Round-Trip Latencies in  
Wireless Networks,  
in Milliseconds*<sup>26,27</sup>



*Exhibit 4-G:  
Publicly Announced 4G  
Wireless Deployments*

Technology	Companies	2009	2010	2011	By 2013
LTE	<ul style="list-style-type: none"> <li>Verizon</li> <li>AT&amp;T</li> <li>MetroPCS</li> <li>Cox</li> </ul>		<ul style="list-style-type: none"> <li>Verizon (100MM)</li> <li>AT&amp;T (Trials)</li> </ul>	<ul style="list-style-type: none"> <li>AT&amp;T (start deployment)</li> <li>Cox (start deployment)</li> <li>MetroPCS (start deployment)</li> </ul>	<ul style="list-style-type: none"> <li>Verizon (entire network)</li> </ul>
WiMAX	<ul style="list-style-type: none"> <li>Clearwire/Sprint</li> <li>Open Range</li> <li>Small WISPs</li> </ul>	<ul style="list-style-type: none"> <li>Clearwire (30MM)</li> <li>WISPs (2MM)</li> </ul>	<ul style="list-style-type: none"> <li>Clearwire (120MM)</li> </ul>		<ul style="list-style-type: none"> <li>Open Range (6MM)</li> </ul>

with HSPA. In addition to the larger providers, there are hundreds of entrepreneurial and independent Wireless Internet Service Providers (WISPs) who provide fixed wireless services to at least 2 million customers in rural areas, including many areas not covered by the national wireless companies.<sup>28</sup> Such deployments are particularly attractive in areas where wired competitors do not exist or have inadequate capabilities.

Fundamentally, FWA uses fixed CPE to deliver better performance by improving end-user signal quality. Examples of techniques that allow fixed wireless to provide superior performance compared to mobile broadband include:

- CPE techniques:
  - Using a higher power transmitter than would be possible with a battery-powered end-user device in order to improve the upstream data rate and/or increase the coverage area
  - Using large high-gain antennas along with external mounting to decrease building loss and further improve both upstream and downstream data rate and/or increase the coverage area
  - Placing the antenna in a favorable location to achieve line-of-sight or near line-of-sight to reduce path loss
- Base Station techniques: using stronger power amplifiers and multiple antenna techniques in order to increase the coverage area and/or capacity

These techniques are broadly applicable to most spectrum bands and to both 3G and 4G technologies. As such, generally speaking, FWA networks can support both fixed and mobile traffic, with fixed CPEs improving the performance of fixed service relative to mobile.

Our objective is to provide fixed broadband service to homes; so, we have used the performance characteristics of a FWA network in our network model. *In what is to follow, unless otherwise mentioned, the term wireless network will refer to a FWA network.*

### Complexity of Analyzing Wireless Networks

It is important to recognize that a wireless network has several layers of complexity that are not found in wireline networks, each of which affect the user experience and, therefore, network buildout costs and the investment gap. For example, the location of the user relative to the cell site has a significant impact on data rates. More precisely, those at the cell edge, i.e., farthest from the cell site, will have much lower signal quality than those closer to it. And as signal quality drops, throughput drops as well; thus, at the cell edge a user may experience more than 60% degradation in data rates relative to the average experience within the cell.<sup>29</sup>

Another factor affecting user experience is the fact that

wireless spectrum is shared by all the users in the cell. As a result, a user can experience significant variations at the same position in the cell depending on temporal changes in capacity demand (or loading).

There are other factors that lead to a heterogeneity of user experience. For example, the wireless signal itself undergoes different levels of degradation depending on terrain, user mobility and location (indoors vs. outdoors vs. in-car). Further, there is a wide range of end-user device types, which vary in their peak bandwidth capabilities, have different types of antennas, form factors, etc. Each of these factors can lead to a different user experience under otherwise identical conditions.

Consequently, analysis of the performance of wireless networks requires a statistical approach under a well-defined set of assumptions. We shall describe the assumptions behind the parameters we used in our wireless network model. However, it is possible that the parameters in an actual network deployment are different from those that we estimated. Improving the accuracy of our estimates would require a RF propagation analysis in the field—an extremely time-consuming and expensive proposition that is usually undertaken only at the time of an actual buildout. And even that approach will not always capture some effects, such as seasonal foliage.

### Approach

Exhibit 4-11 is a schematic that lays out our approach to analyzing the cost of the network buildout. The cost of the network, as shown, is driven by the number of cell sites required to deliver broadband service and the cost of building, operating and maintaining each cell site.

The number of cell sites required to serve an area is fundamentally dependent on capability of the technology. Using the performance of LTE networks, we dimension cell sites to deliver downlink and uplink speeds of 4 Mbps and 1 Mbps, respectively, in two steps:

- First, we ensure that the cell sizes are dimensioned to provide *adequate signal coverage*; i.e., absent any capacity limitations, the propagation losses within the coverage area are constrained and, therefore, the received signal strengths are adequate for delivering the target data rates. Our analysis indicates that the uplink requirement is the driver of coverage limitations.
- Next, once we have ensured adequate signal coverage, we ensure that each cell site has sufficient *capacity* to meet the traffic demand. We achieve this by constraining the maximum number of subscribers per cell site. As mentioned in Network Dimensioning, we only consider the downlink capacity requirements—and not the uplink—for our analysis.

Following that, we present the economics of a wireless network. In particular, we analyze the influence of factors like spectrum, terrain and downlink capacity on wireless economics. We also discuss in detail the factors that influence the cost of building and operating a cell site, namely tower lease/construction and backhaul for cell sites.

### Dimensioning the Network for Coverage

The method of determining the maximum cell radius to ensure sufficient coverage in the modeled network is driven by three key factors (see Exhibit 4-I):

- **Broadband rate targets and the corresponding link budgets:** Link budgets allow us to calculate the Maximum Acceptable Propagation Loss (MAPL) of the transmitted signal such that the received signal quality is adequate for achieving the target data rates.
- **Spectrum bands:** The propagation characteristics of spectrum bands are different, thereby impacting cell radius.
- **Terrain:** It plays an important role in radio propagation. Simply put, mountains and hills block wireless signals; so areas with rougher terrain require smaller cell radii than areas with flat terrain.

### Link Budgets

In order to deliver uplink speeds of 1 Mbps within 90% of the cell coverage area in a FWA network, the maximum acceptable propagation loss (MAPL) is 142 to 161 dB; see highlighted text

in Exhibit 4-J. By contrast, the MAPL in a mobile environment is 120 to 132 dB. In other words, higher power CPEs with directional antennas placed in favorable locations in a FWA network yield gains of more than 20 dB over mobile devices.<sup>30</sup>

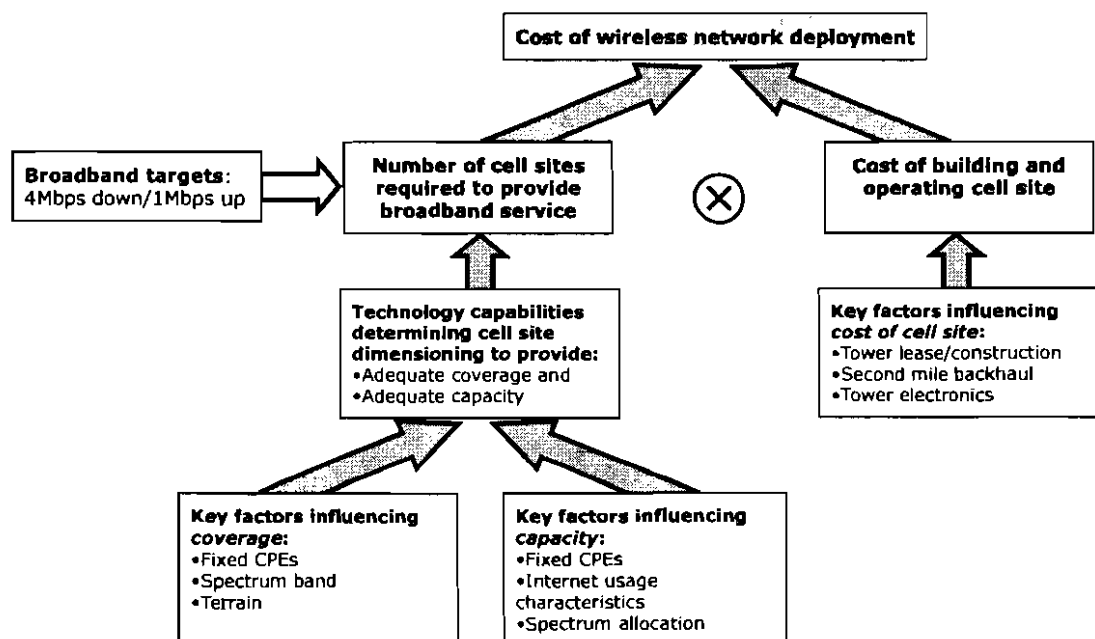
For our target data rates, it is the uplink that drives coverage limitations; i.e., the cell radius limits imposed by the uplink link budget calculation are smaller than the radii required to ensure adequate downlink received signal strengths. A cell radius small enough for a 200 mW handheld device or a 500 mW FWA device to deliver adequate signal strength to the base station is also small enough for a 40 W (macro) base station to deliver more than adequate downlink signal strengths.

Loosely speaking, unless the downlink and uplink requirements are more asymmetric than the power differential, the significantly higher power at the base station implies that adequate uplink coverage should result in adequate downlink coverage.<sup>31</sup>

### Impact of spectrum bands

Cellular service today typically operates in one of several bands: from 700 to 900 MHz; from 1.7 to 2.1 GHz; and from 2.5 to 2.7GHz (see Chapter 5 of National Broadband Plan for details). Generally speaking, in this range of frequencies lower frequency signals suffer lower propagation losses and therefore travel farther, allowing larger cell sizes. Lower frequency signals also penetrate into buildings more effectively. Thus, for example, the Okumura-Hata model<sup>32</sup> predicts that the radius of rural cells in the 700MHz band can be as much as 82% greater

Exhibit 4-11:  
Approach for  
Analyzing Cost of  
FWA Network



than in the PCS band for comparable coverage. In suburban areas this benefit is 105%, while in urban areas the improvement is greater than 140%. That makes lower frequency bands better suited for coverage and deployments in rural areas.

Terrain classification and maximum cell size

Terrain plays an important role in radio propagation, an effect that cannot be captured using propagation loss models such as

the Okumura-Hata model.<sup>33</sup> Since mountains and hills block wireless signals, areas with rougher terrain require smaller cell radii than areas with flat terrain.

To account for this effect of terrain, we classified terrain into each of the four categories shown in Exhibit 4-K. More precisely, we used GIS data to classify each Census Tract (CT),<sup>34</sup> based on elevation variations across one square Km grids, into one of the four categories.

Exhibit 4-I:  
Methodology  
for Determining  
Maximum Cell  
Radius for Coverage

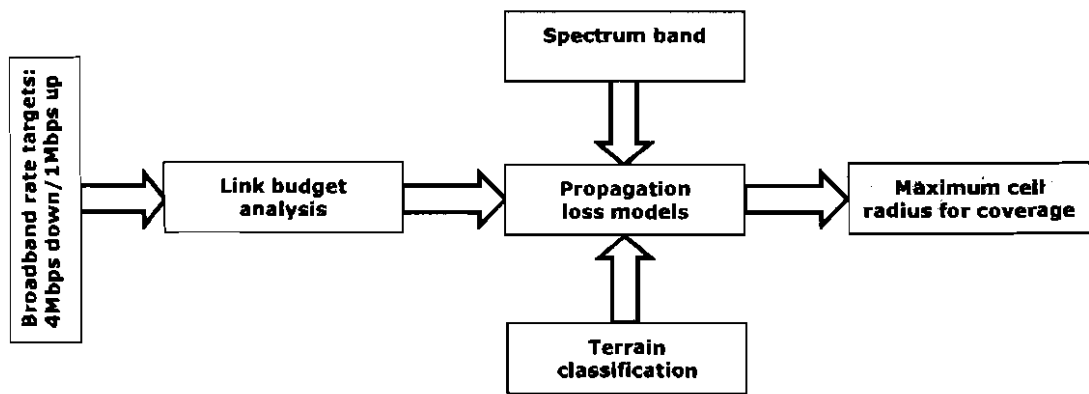
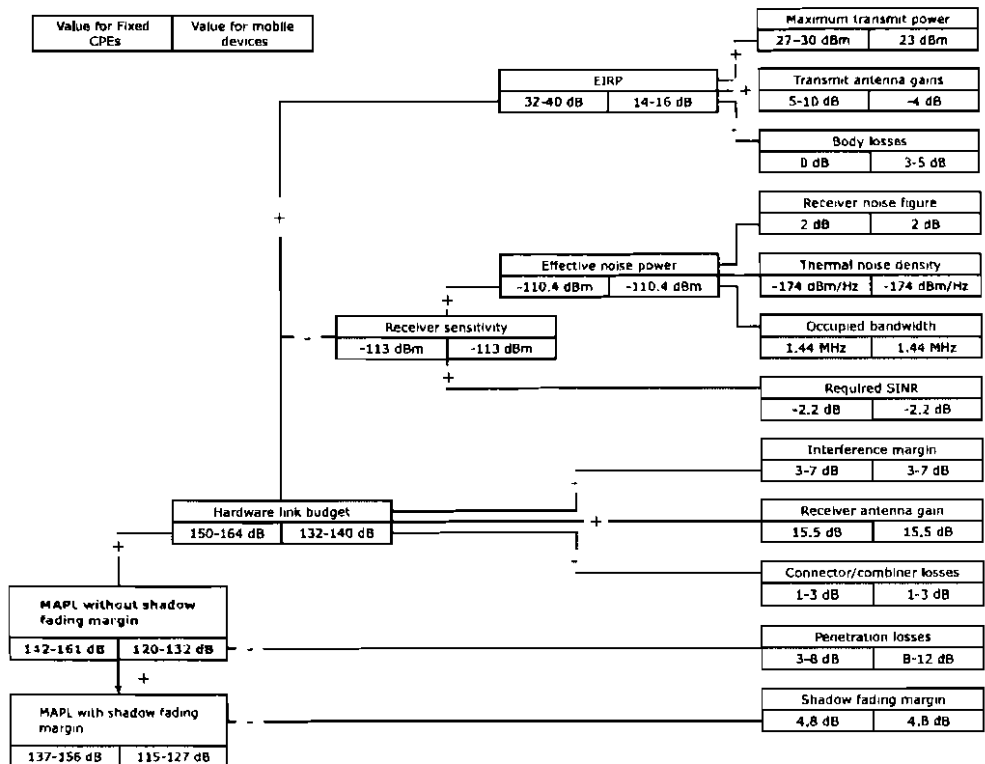


Exhibit 4-J:  
Link Budget for  
Delivering 1.26  
Mbps Uplink Speeds  
at 700MHz<sup>47,36</sup>



Recall from the discussion of link budgets that the Maximum Allowable Propagation Loss (MAPL) for achieving our target broadband speeds is 142–161 dB. We use RF planning tools<sup>37</sup> (see Exhibit 4-M) to estimate the cell radius for each terrain type that will keep propagation losses within

bounds.<sup>38</sup> More specifically, we choose the MAPL to be 140 dB, allowing for possible propagation losses due to foliage.<sup>39</sup> Areas in green in Exhibit 4-M correspond to areas with adequate signal coverage. The results of this analysis are shown in Exhibit 4-L for the 700MHz band.

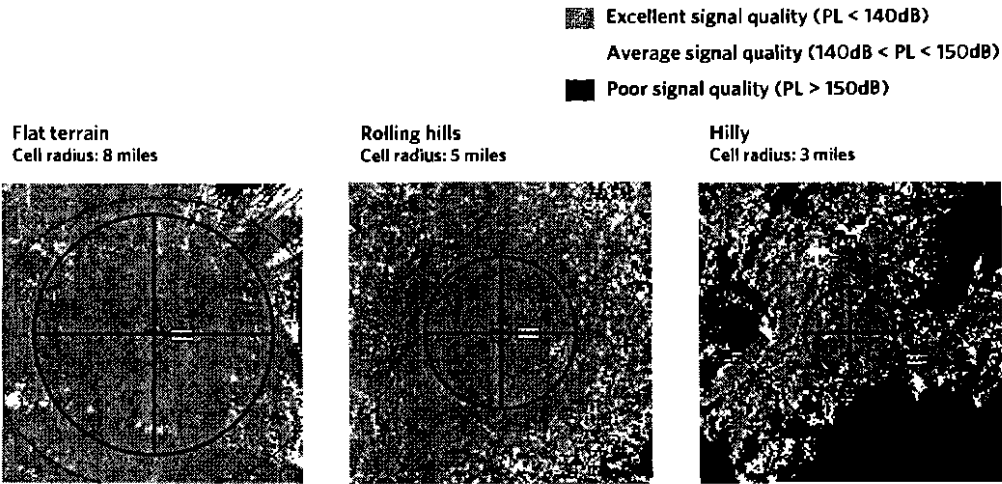
Exhibit 4-K:  
Classification of Terrain  
of Census Tracts

Terrain type	Standard deviation (SD) of elevation (meters)	Examples
Flat	≤ 20	Topeka, Kan.; SD = 12 King City, Mo.; SD = 19
Rolling hills	20 to 125	Manassas, Va.; SD = 41 Lancaster, Pa.; SD = 45
Hilly	125 to 350	Lewisburg, W.V.; SD = 167 Burlington, Vt.; SD = 172
Mountainous	≥ 350	Redwood Valley, Calif.; SD = 350

Exhibit 4-L:  
Maximum Cell Radius  
for Adequate Coverage  
in the 700MHz Band

Terrain type	Examples	Maximum cell radius (miles)
Flat	Topeka, Kan. King City, Mo.	8
Rolling hills	Manassas, Va. Lancaster, Pa.	5
Hilly	Lewisburg, W.V. Burlington, Vt.	3
Mountainous	Redwood Valley, Calif.	2

Exhibit 4-M:  
Propagation Loss for  
Different Terrain Types  
at 700MHz<sup>40</sup>



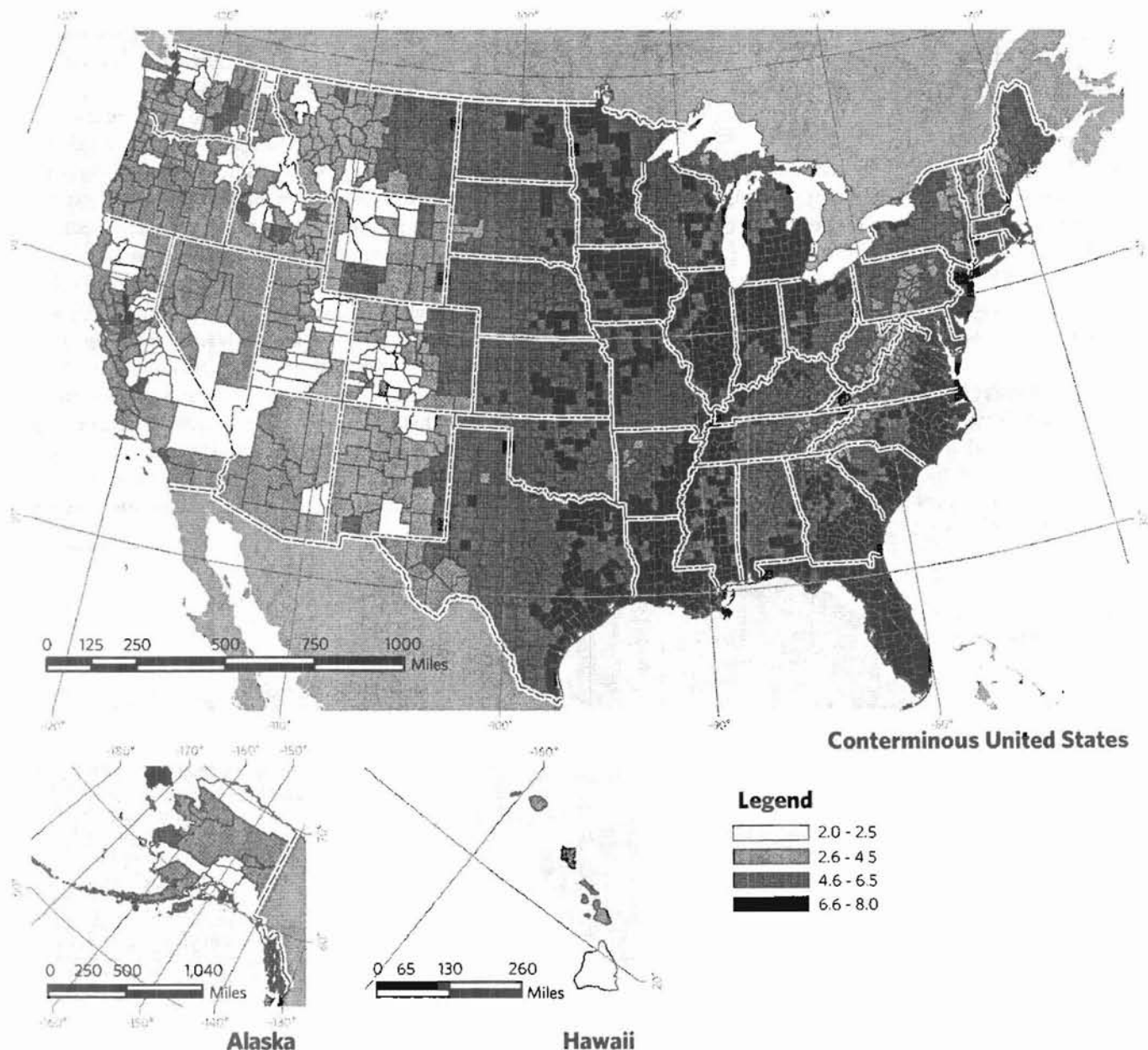


We show a terrain map of the continental United States in Exhibit 3-X; average cell radii for each county based on the classification in Exhibit 4-L for the 700MHz band are shown in Exhibit 4-N. Finally, Exhibit 4-O quantifies the number of households by the cell sizes required to provide adequate

coverage to them. Note that only around 13% of housing units (HUs) are in hilly or mountainous areas.

Finally, the propagation characteristics of the spectrum band clearly impact coverage. But, spectrum availability does not play an explicit role in our analysis. Certainly the

*Exhibit 4-N:*  
*Average Cell Size in Each County (in miles)*



aggregated uplink *capacity* at a cell site improves with spectrum, but the only way to increase the maximum achievable data rate for a *specific user* is to reduce cell size. In other words, site counts will increase if we increase the uplink data rate requirement; adding more spectrum will not alleviate the problem.

#### Dimensioning the Network for Capacity

Exhibit 4-P shows that subscriber capacity of the wireless network depends primarily on the following:

- Broadband requirements and traffic characteristics. The first represents the National Broadband Availability Target of 4 Mbps downlink while the latter is a characterization of the demand for network capacity, generated by the subscribers on the network (see also Network Dimensioning section).
- Spectrum allocation. Loosely speaking, if spectral efficiency of the air interface remains unchanged, capacity of the wireless network grows proportionately with spectrum allocation.
- Fixed CPE with directional antennas. Specifically, the improvement in signal quality and data rates resulting from using directional antennas at CPE.

We then use the performance of LTE networks to determine the maximum subscriber capacity of the FWA network.

Importantly, signal quality or Signal to Interference and Noise Ratio (SINR)<sup>41</sup> in the downlink is not significantly impacted by increasing the transmission power in cells that are

not coverage (i.e., signal strength) limited. This is because signal attenuation depends on the distance from the transmitter, so that SINR depends on the distance of the user from the *serving*<sup>42</sup> cell site relative to the other interfering cell sites. So, if we increase transmission power of all cells similarly, both received signal power and interference power increase proportionately and the net improvement in SINR is small. Correspondingly, reducing the radius of all cell sites proportionately also has a relatively small impact on SINR distribution.

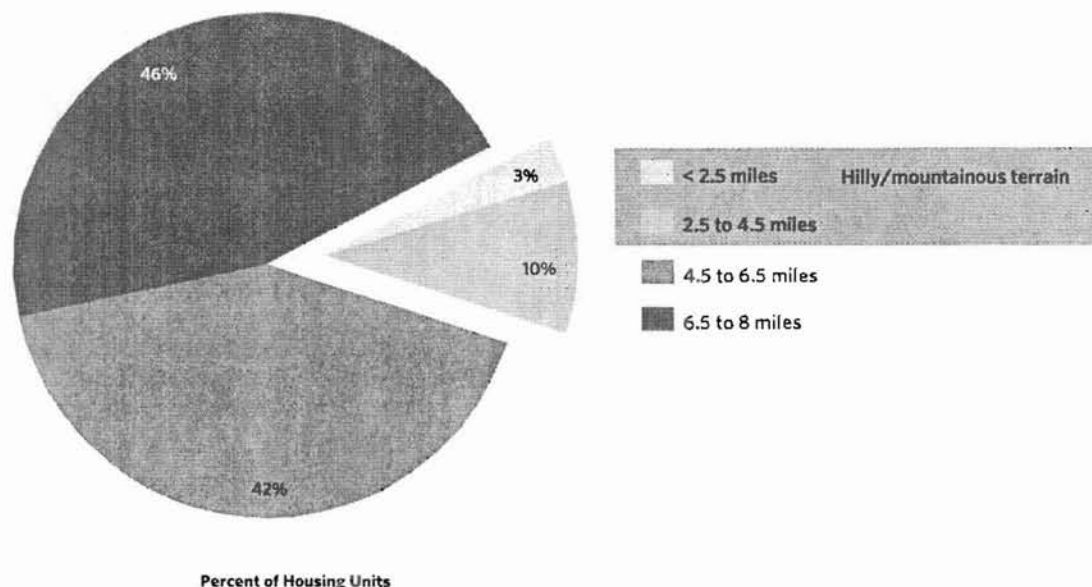
#### Requirements and Traffic Characteristics

Exhibit 4-Q shows our estimate of the maximum number of subscribers in a FWA cell site for different spectrum allocations.<sup>43</sup> This estimate includes the impact of directional antennas in fixed CPE as discussed below.

As noted in the section on coverage, cell radii are chosen to ensure that the signal quality is adequate for delivering 4 Mbps downlink and 1 Mbps uplink. However, since spectrum is a shared resource, we must ensure that the network is also capable of providing sufficient capacity to deliver these speeds. The approach to sizing the number of subscribers therefore is to first characterize network usage using the Busy Hour Offered Load (BHOL) metric; see Network Dimensioning for details. We assume the BHOL per subscriber is 160 kbps. Then, we use the performance of LTE networks to determine the maximum number of subscribers per cell site for different spectrum allocations such that users achieve the broadband-speed target 95% of the time when the BHOL is 160 kbps.<sup>44</sup>

Note that we achieve our target downlink data rate by limiting the maximum subscribers per cell site, which can be

Exhibit 4-Q:  
Coverage of  
Unserved Housing  
Units by Cell Radius



interpreted to be a limit on cell size. But we remarked earlier that we cannot increase data rates by reducing cell size—a seeming contradiction. The resolution is that reducing cell size does not improve signal quality unless it results in a reduction in the number of subscribers per cell site. For example, the user-experience in two cells with 100 subscribers each will not be materially impacted if the cell radius of each is 1/2 km instead of 1 km. Since the load on the network will not change in either case, the utilization is unchanged as well. If we now introduce two additional cells into this hypothetical network, such that each cell has 50 subscribers, then we will see an improved user experience because fewer subscribers in each cell will imply reduced load in each cell. That, in turn, will reduce each cell's utilization and, thereby, improve signal quality and

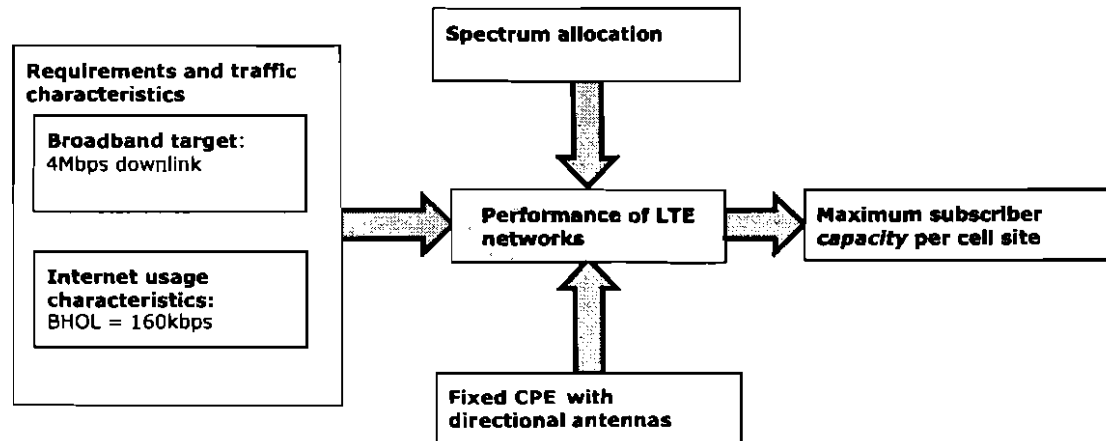
end-user data rates.

So, we cannot prescribe a maximum cell radius to achieve a target downlink data rate (because population density across geographies is not uniform). But we can limit subscribers per cell to achieve target speeds.

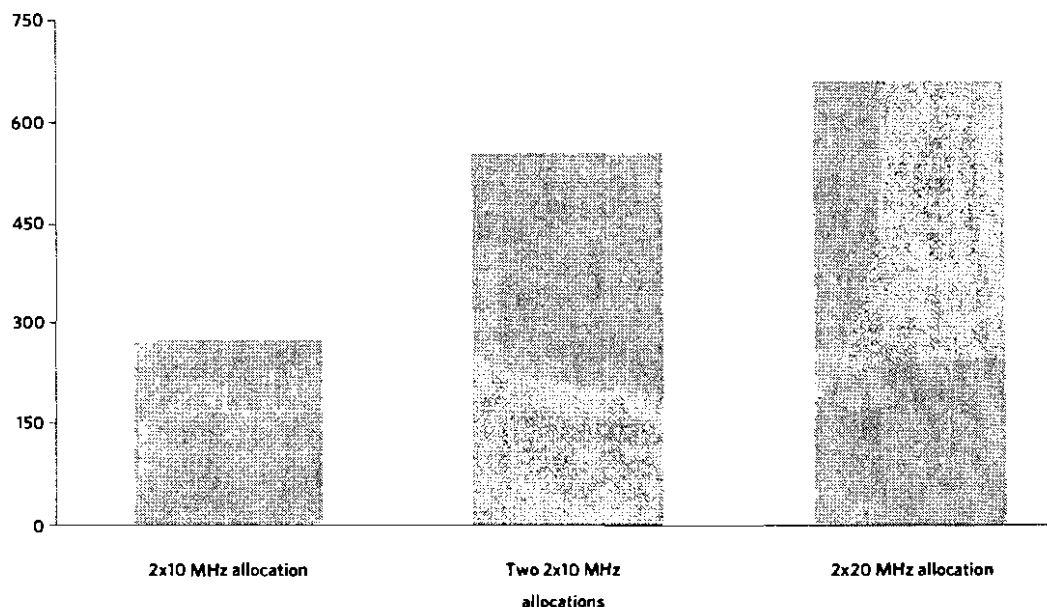
#### Fixed CPE with directional antennas

Using fixed CPE with directional antennas can result in more than a 75% improvement in spectral efficiency over CPE with omni-directional antennas.<sup>42</sup> More significant is the gain in data rates at the cell edge. We illustrate this in Exhibit 4-R. Specifically, the chart on the left shows the improvement in SINR distribution in the cell site when the network has CPE with directional antennas instead of omni antennas. For

*Exhibit 4-P:  
Methodology for  
Dimensioning  
Wireless Networks  
to Provide Adequate  
Capacity*



*Exhibit 4-Q:  
Maximum Number  
of Subscribers  
Per Cell Site in  
an FWA Network  
with Directional  
Antennas at the  
CPE<sup>46</sup>*



example, nearly 35% of users in a network with omni antennas have a SINR of 0 dB<sup>47</sup> or worse. By contrast, less than 1% of the users in a network with directional antennas have a SINR of 0 dB or worse. The significant boost in signal quality is a result of (a) improved signal reception with the higher antenna gain of a directional antenna and (b) reduced interference due to the increased interference rejection possible with such antennas.

This improvement in SINR directly translates to better data rates. For example, if a CPE with an omnidirectional antenna experiences a data rate of ~3 Mbps, then a CPE with a directional antenna will experience an average of ~9 Mbps under otherwise identical conditions.

### Spectrum allocation

We mentioned above that lower spectrum bands are better suited for coverage. Higher frequency spectrum, on the other hand, is better suited for capacity by deploying Multiple Input and Multiple Output, commonly referred to as MIMO,<sup>48</sup> solutions. This is because smaller antennas can be used at higher frequencies and multiple antennas can be more easily integrated into handsets constrained by form factor. As such, deployments in these bands can have higher spectral efficiency. That is not to say that MIMO cannot be deployed in the lower frequency bands; rather, MIMO solutions are more practical and cheaper in the higher bands.

In our model, we assume 2x2 MIMO,<sup>49</sup> which is easily implemented in the 700MHz band in a FWA network.

The importance of spectrum towards ensuring a robust mobile broadband future has been discussed at length in the

Chapter 5 of the NBP. In this section, we discuss how spectrum availability impacts subscriber capacity. For convenience, we shall assume the propagation characteristics of the 700MHz band for this discussion.

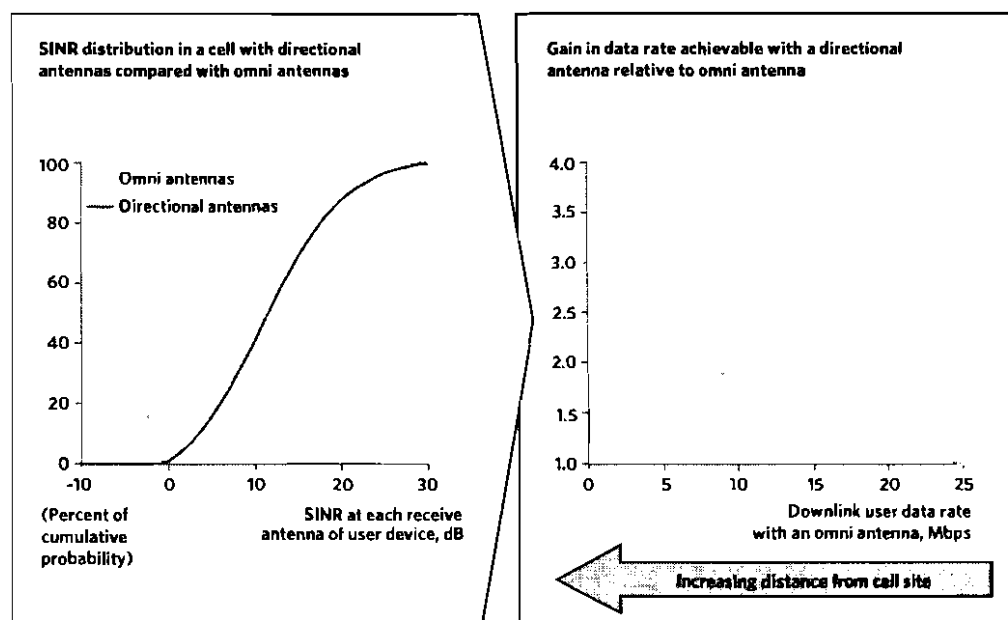
In Exhibit 4-Q, we saw that the capacity of a network with two paired 2x10MHz carriers<sup>50</sup> is twice that of a single 2x10MHz carrier. That should not be surprising. Interestingly, however, the capacity with a single 2x20MHz carrier is 20% higher than with two 2x10MHz carriers.<sup>51</sup> This is, in part, due to the better statistical multiplexing possible with the first option (using the wider carrier). Most of these gains will also be achievable with the second option once carrier/spectrum aggregation is introduced in the LTE standard.

Exhibit 4-S shows the spectrum needs in 2020 and 2030 for coverage cell sites in the unserved regions of the United States. Recall that coverage cell sites provide adequate downlink and uplink coverage (i.e., 4 Mbps/1 Mbps downlink/uplink speeds at the cell edge); however, depending on the number of households within the cell site, it may not have enough capacity to meet the traffic needs.

For our baseline model, we assume that 2x20MHz of spectrum is available per cell site. So, as the figure shows, in 2020, 94% of the coverage cell sites will also have adequate capacity. The remaining cells need techniques such as cell-splitting or 6-sector cell sites to increase capacity.<sup>52</sup> As the uptake continues to increase, the spectrum needs will also increase, as shown by the chart on the right.

*This analysis is based on an average BIOL per subscriber of 160 kbps. Higher data usage than that will indeed increase spectrum needs. Still, the analysis shows that spectrum needs are*

*Exhibit 4-R:  
Impact of  
Directional  
Antennas at CPE on  
SINR*<sup>53,54</sup>



relatively modest, due to three reasons. First, we used a FWA network, which has higher capacity than a mobile one. Second, the population density in the unserved regions is very low—less than 10 HUs per square mile. Consequently, the number of subscribers per cell site and the traffic demand per cell site are also relatively modest. Finally, the uplink coverage requirement of 1 Mbps resulted in a much higher cell site density than would otherwise be necessary, which further reduced the number of subscribers per cell site.

We end this discussion on spectrum availability by contrasting the difference in impact spectrum has on uplink and downlink dimensioning:

- In order to achieve a target *uplink* user data rate, we limit the maximum cell radius to ensure sufficient *coverage*. And while propagation characteristics of the spectrum band are important for our calculation of maximum cell radius, spectrum availability has little impact—the uplink signal received at the cell tower, not the availability of spectrum, is the limiting factor.
- In the *downlink*, on the other hand, we are limited by cell site *capacity*. We can either reduce the cell size to match subscriber demand with capacity, or we can add spectrum to the cell site, because more spectrum implies more capacity. The first option is more expensive, because the incremental cost of using additional spectrum at a cell site is smaller than the construction costs associated with cell-splitting if spectrum is available.

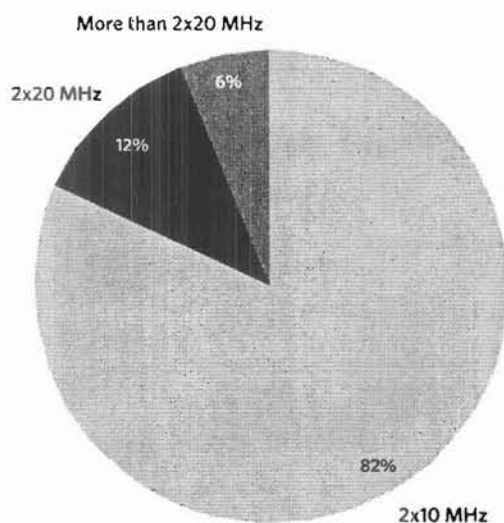
Therefore, the overall impact of spectrum availability on network buildout depends on the evolution of downlink and uplink usage characteristics. Specifically, let us consider two extreme scenarios:

- **Extreme uplink usage:** If uplink usage were to evolve disproportionately faster than the downlink, then the only way to dimension the network would be to reduce the cell size. In doing so, we reduce the number of subscribers per cell site. That, in turn, automatically reduces the downlink capacity needs per cell site so that spectrum plays a less critical role in the solution.
- **Extreme downlink usage:** If, on the other hand, downlink usage evolves disproportionately faster than the uplink, then availability of spectrum can significantly mitigate the need for additional cell sites. That, in turn, significantly reduces the cost of network capacity expansion.

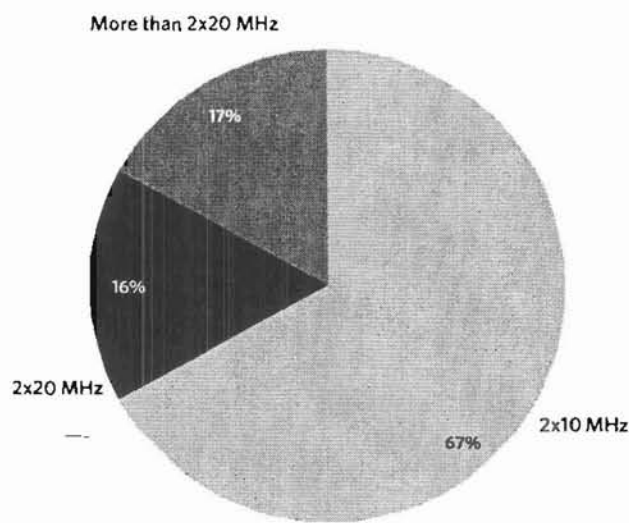
### Second-Mile Backhaul

A key requirement of wireless broadband networks is high-capacity backhaul, a need that will only grow as end-user speed and effective load grow. Today, even though 97.8%<sup>55</sup> of the U.S. population has 3G coverage, most cell sites are still copper fed. For example, Yankee Group estimates that more than 80% of cell sites are copper fed.<sup>56</sup> Further, Sprint Nextel noted that in its network, “most towers carry between one and three

*Exhibit 4-S:  
Spectrum Needs for  
Cell Sites in 2020  
and 2030, Based on  
BHOL of 160 kbps*



Spectrum needs for cell sites, 2020  
Percent of cell sites



Spectrum needs for cell sites, 2030  
Percent of cell sites

DS-1s” and that “almost no towers have more than five DS-1s.”<sup>57</sup> This is important because copper facilities will have inadequate speeds for a well-subscribed 4G cell site; so, without adequate upgrades, backhaul can quickly become the choke point of the network (see Exhibit 4-T). Additionally, both fiber and microwave avoid some of the reliability problems often found in dealing with copper-based backhaul. Said differently, dimensioning adequate backhaul is one of the key drivers for providing wireless broadband. As shown in Exhibit 4-T, for our purposes we need backhaul capacity that can only be provided by fiber and/or microwave.

In unserved areas, microwave point-to-point backhaul is a potentially attractive alternative to fiber for providing second-mile capacity at substantial cost savings relative to fiber. We assume that microwave allows high-capacity connectivity at a lower price by bypassing the need for a direct aerial or trench-based connection. For instance, a microwave link can provide speeds of up to 500 Mbps over a distance of 20 miles<sup>58</sup> at a typical equipment cost of roughly \$50,000.<sup>59</sup>

By contrast, costs of new fiber construction depend heavily on the distance to an existing fiber network and whether the area has aerial plant available for connection. Costs can range from approximately \$11,000 to \$24,000 per mile for aerial construction and roughly \$25,000 to \$165,000 per mile for buried construction.<sup>60</sup> Many providers may prefer fiber regardless of the cost, especially in denser areas, because of its ability to provide higher capacity per link and its inherent reliability.

Overall, when compared with new fiber construction, and even with leased Ethernet links, microwave links can have a

lower total cost for link distances greater than 1-2 miles.<sup>61</sup>

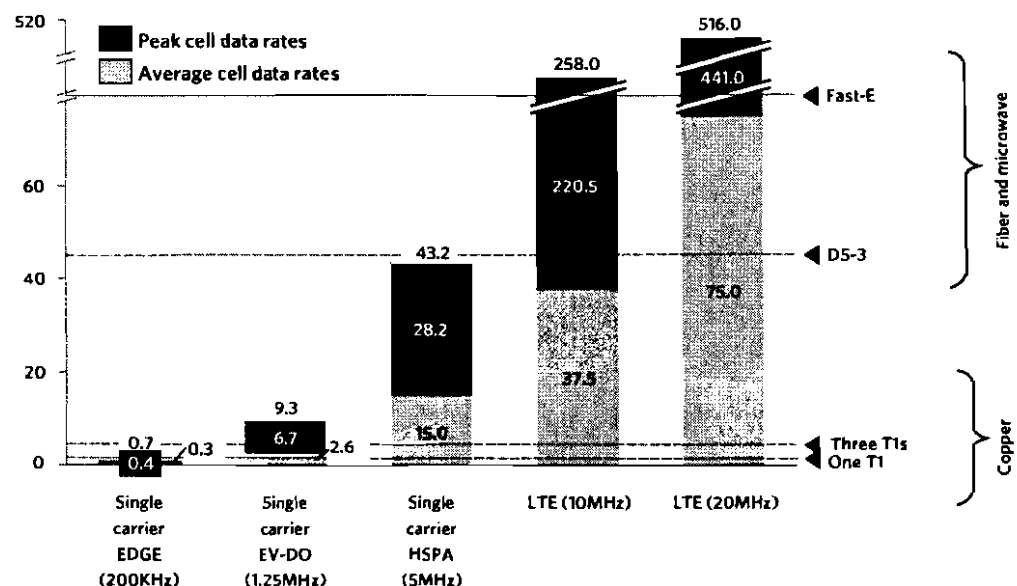
Ethernet over Copper (EoC) may also be part of the 4G-backhaul solution. We did not include EoC in our 4G-backhaul calculations for several reasons: first, as noted above, there is often a limited amount of copper available; second, the quality of that copper over the multi-mile distances in rural areas is unknown; and third, for new cell-site construction, where there are no existing backhaul facilities, carriers are likely to install fiber or rely on microwave.

#### Hybrid Fiber Microwave (HFM) backhaul architecture

Since microwave can be a cost-effective substitute for fiber, a Hybrid Fiber Microwave (HFM) backhaul architecture would yield significant cost savings in wireless networks relative to an all fiber network (see Exhibit 4-U). Specifically, as illustrated in the exhibit, in an HFM architecture some cell sites rely on microwave for backhaul, and only few cell sites are fiber-fed. The fiber-fed sites serve as backhaul “aggregation points” for the remaining cell sites. These remaining sites connect to the fiber-fed aggregation points using microwave links, sometimes using more than one microwave hop. For example, Cell site 3 is fiber fed, serving as an aggregation point for the backhaul needs of Cell sites 1 and 2. Further, Cell site 2 connects to Cell site 3 using one microwave hop, while Cell site 1 connects using two (via Cell site 2). Such HFM architectures are already being used by wireless service providers such as Clearwire, for example.<sup>62</sup>

Even though the microwave links now have reliability comparable with their wireline counterparts, an HFM network that uses a large number of hops can lead to concerns about

Exhibit 4-T:  
Average and Peak  
Capacity of a 3-Sector  
Cell Site Relative to  
Backhaul Speeds, Mbps



reliability. To see this, observe in Exhibit 4-U that the loss of the microwave link between Cell sites 2 and 3 will also result in the loss of backhaul connectivity for Cell site 1. If each of these cell sites had a radius of 5 miles, then as much as 150 square miles would lose coverage through the loss of the single link. Clearly, then, this cascading effect can become particularly pronounced in a network that has a large number of hops. On the other hand, the more hops, the greater the potential for second-mile cost savings.

Our baseline model for FWA uses an HFM architecture with a maximum of four microwave hops.

In unserved areas, an IIFM second-mile network architecture has cost advantages over a fiber-only network architecture. Microwave backhaul has two additional benefits, especially to service providers who do not already own fiber middle-mile backhaul assets. First, microwave can often be deployed faster than fiber. Second, in many territories, the owner of wired backhaul facilities could be a competitor in providing wireless service. In such cases, microwave backhaul offers an effective alternative to paying competitors for backhaul service.

However, microwave backhaul also has two significant limitations. First, as noted earlier, microwave links have capacity limitations and cannot be used for very high-speed backhaul needs. Further, higher data rates require more spectrum. Since there is only a limited amount of spectrum available, carriers can only have a limited number of high-speed microwave links in a geographical area. Note that the NBP had a series of

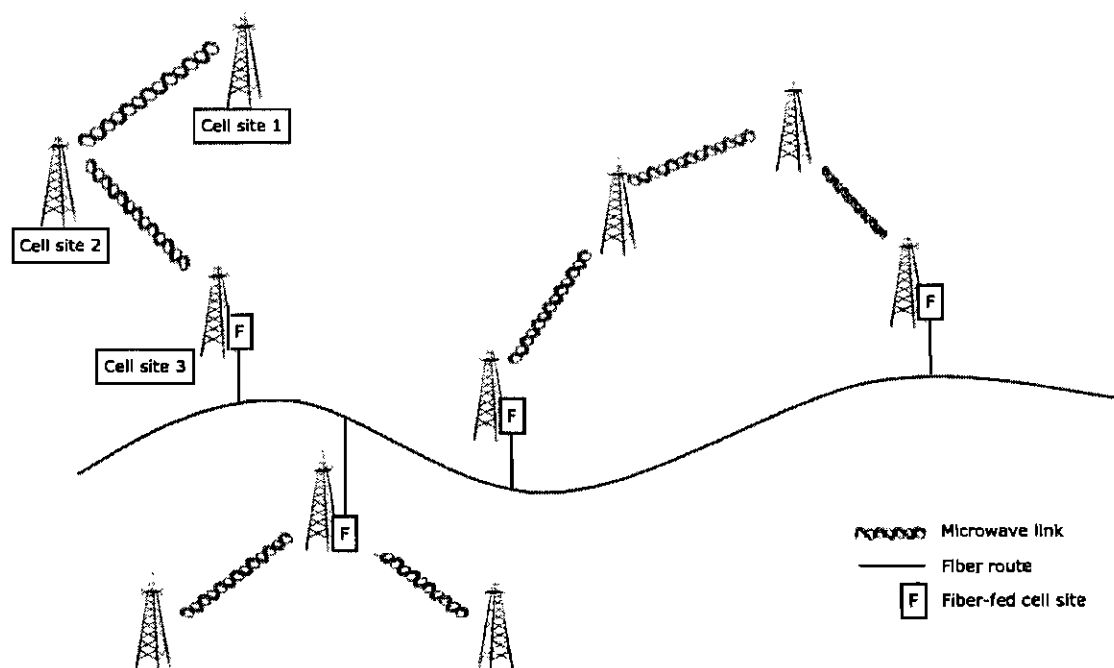
recommendations related to improving point-to-point backhaul solutions in Chapter 5.

The second limitation is a requirement for line of sight from one microwave tower to the next. In hilly or mountainous terrain, this may mean that a provider needs to add additional microwave relays even beyond the reduction in cell size described above, adding to costs. It may be the case that the same terrain issues drive up fiber costs as well, perhaps even more quickly, so this will not necessarily tip the balance toward fiber. But it will likely drive up backhaul costs overall. Further, in some cases the tower may need structural reinforcements to support a microwave antenna, which will drive up the cost of microwave installation.

So, even though an HFM architecture has significant cost advantages, fiber is expected to be the primary backhaul choice for service providers because it offers a scalable, future-proof backhaul solution.

Finally, a fiber-only architecture has one significant strategic advantage. As broadband needs continue to grow, fiber emerges as the only last-mile technology capable of meeting ultra high-speed needs. So, any solution that brings fiber closer to the home by pushing it deeper into the network puts into place an infrastructure that has long-term strategic benefits. On balance, therefore, we need to weigh this strategic benefit against the higher associated cost to evaluate the value of a fiber-only architecture over an HFM architecture.

*Exhibit 4-U:  
Hybrid Fiber  
Microwave  
Backhaul  
Architecture for  
Cellular Networks*



### Economics of a Wireless Network

Exhibit 4-V shows the network elements that we modeled for FWA network cost analysis (see also Exhibit 4-A above). Specifically, in the last mile—the link from the cell site to the end-user—we model installation and operations costs, as appropriate, for the tower infrastructure, Radio Access Network (RAN) and other ancillary<sup>63</sup> equipment. We also account for the cost of the end-user CPE. In the second mile, which is the backhaul connection from the cell site to the second point of aggregation in the exhibit, we model the costs of installing microwave equipment and new fiber, as needed; see the Section on Middle Mile for details on backhaul network architecture.

Our network model, as shown in Exhibit 4-V, shows that the Investment Gap when using FWA networks in the 700MHz band for providing broadband to the unserved population in the United States is \$12.9 billion (Exhibit 4-W). This funding gap is for the wireless buildout *only* and is not driven by the second least-expensive of a mix of technologies. For more details on our overall network modeling assumptions and principles, see **Creating the Base-case Scenario and Output** above.

### Dependence on terrain type

Recall that for our network model, we classify terrain into four types, choosing a different maximum cell radius for each. Exhibit 4-X shows the average investment (i.e. capex) per housing unit (HU) and Investment Gap per HU based on the underlying cell radius required. The smaller cell radii

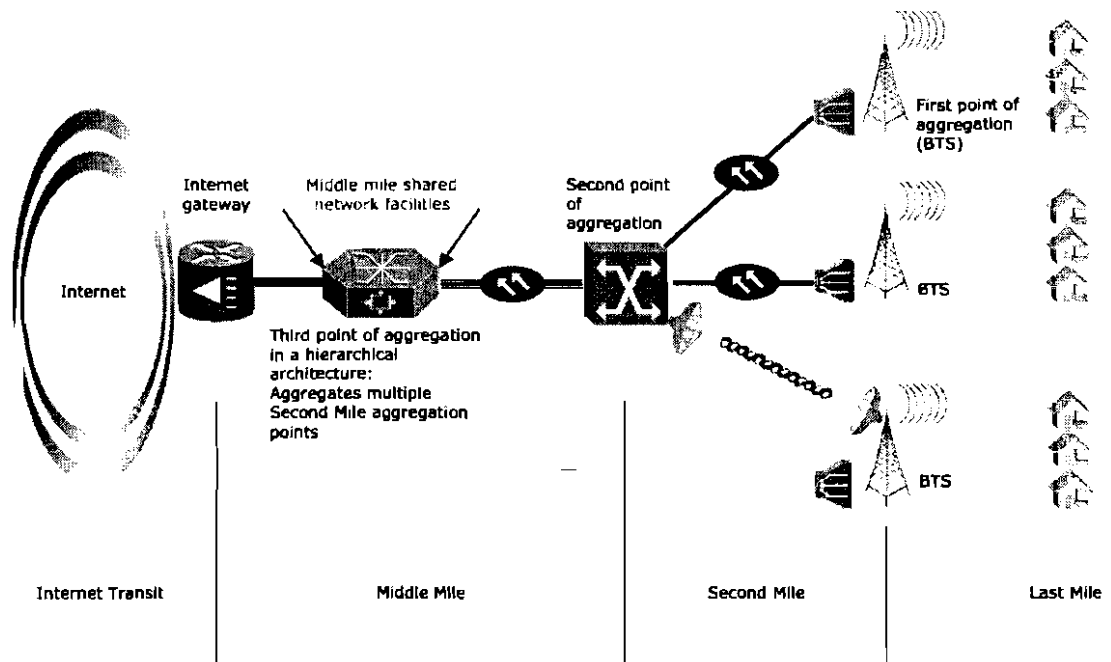
correspond to counties that are mountainous/hilly.

The exhibit shows that the cost of serving HUs in hilly terrain can be as much as 30 times higher on average than in flatter areas. This is in part due to the fact that smaller cell radii in hilly terrain mean that we need more cell sites, thereby driving up the cost; and, in part due to the fact that HU density is also lower in hilly areas.<sup>64</sup>

Our classification of terrain in Exhibit 4-K is based on a statistical analysis of terrain variation data. It is likely that in some instances our method will misclassify a census tract (CT). The only way to get an extremely accurate estimate of cell radius is to actually do a RF propagation analysis for each CT using tools such as those provided by EDX Wireless. That is extremely time-consuming and expensive. To range the impact of misclassification, we analyze the sensitivity of buildout costs and the investment gap to our terrain classification parameters.

Exhibit 4-Y illustrates the results from our sensitivity analysis. In addition to the FWA buildout costs and the FWA investment gap, we also show the overall investment gap for bringing broadband to the unserved using a mix of technologies. Note that the impact on the overall investment gap is less than 10%. This is because the overall investment gap is driven by the second least-expensive technology. More specifically, we find that the percentage of unserved HUs served by wireless drops from 89.9% in the baseline to 89.1% with the “very mountainous” classification in parameter C, thus explaining the relatively small impact terrain classification has on the overall investment gap.

Exhibit 4-V:  
Illustrative  
Wireless Network  
Architecture





**Dependence on downlink capacity**

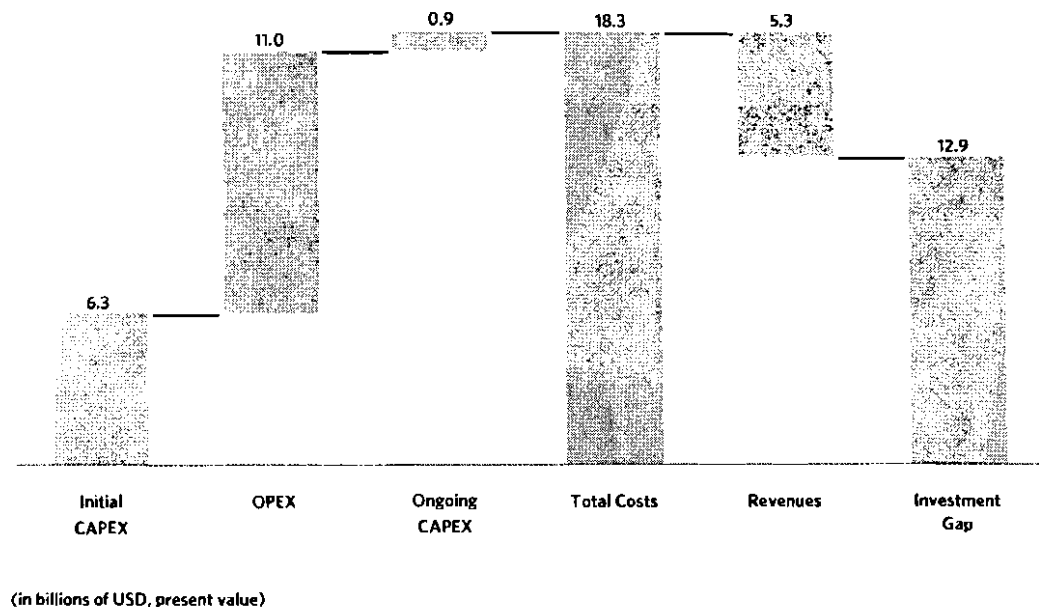
Since LTE is not commercially deployed yet, it is conceivable that actual downlink spectral efficiency and, consequently, subscriber capacity differ from that simulated. So, we analyze the dependence of wireless buildout costs and the investment gap to our subscriber capacity estimates as shown in Exhibit 4-Z. We note that the impact on costs as well as Investment Gap is

negligible. Consequently, the impact on the overall Investment Gap—as determined by the cost of the second least-expensive network—is also small (not shown in chart).

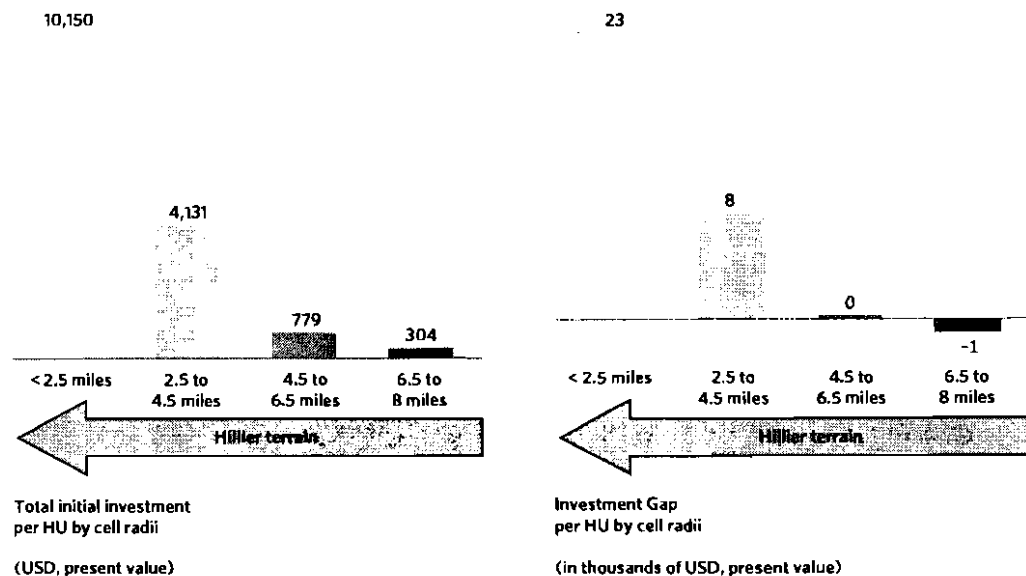
**Dependence on spectrum**

Our baseline model assumes a network deployment in the 700 MHz band. If, instead, we deploy the network in the PCS band, the

*Exhibit 4-W:*  
*Investment Gap for*  
*Wireless Networks*



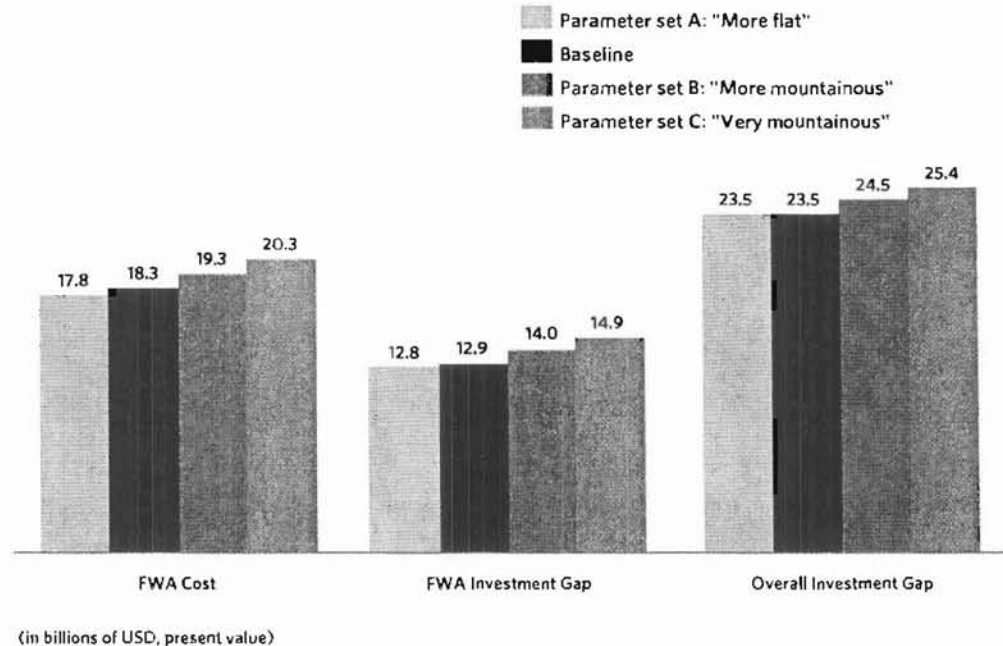
*Exhibit 4-X:*  
*Total Investment per*  
*Housing Unit (HU) and*  
*Investment Gap per HU*  
*by Cell Size*



total cost of the FW deployment in counties with negative NPV is 96% greater. Further, the FW investment gap is 90% more. Note that this is a comparison of the FW investment gap only and not that of the overall investment gap. For this analysis, we use the following maximum cell radius for each of the four terrain types.<sup>65</sup>

Terrain classification	Maximum cell radius (miles)
Flat	5
Rolling hills	3
Hilly and Mountainous	2

*Exhibit 4-J:*  
*Sensitivity of Investment Gap to Terrain Classification—Change in Costs and Investment Gap by Changing Terrain Classification*<sup>66</sup>



Terrain type	Classification parameters based on Standard Deviation of elevation of CTs			
	Baseline	Parameter set A	Parameter set B	Parameter set C
Flat	≤ 20	≤ 25	≤ 20	≤ 20
Rolling hills	20 to 125	25 to 125	20 to 125	20 to 125
Hilly	125 to 350	125 to 350	125 to 300	125 to 250
Mountainous	≥ 350	≥ 350	≥ 300	≥ 250

Cost and gap shown for counties that have a negative NPV. The baseline classification is based on parameters in Exhibit 4-K. The remaining parameter sets alter the classification of flat and hilly terrains, as shown below. We highlight the changes in the parameters from the baseline for convenience.